Hadronic Structure and Neutrino Interactions at the Forward Physics Facility

Juan Rojo, VU Amsterdam & Nikhef

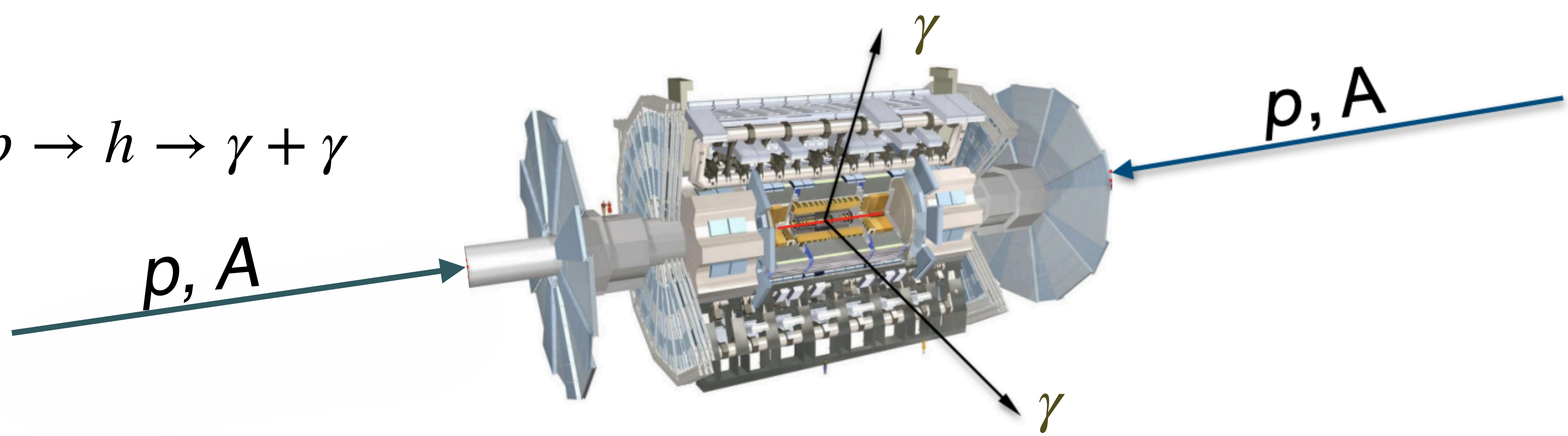
Neutriverse Workshop: A Universe of Neutrinos, 30.11.2022

a Forward Physics Facility at the High-Luminosity LHC

The LHC as a neutrino factory

- The ATLAS and CMS detectors were designed with a focus on **identifying weak-scale and heavier particles**, whose decay products lie in the **central rapidity** acceptance region

$$p + p \to h \to \gamma + \gamma$$



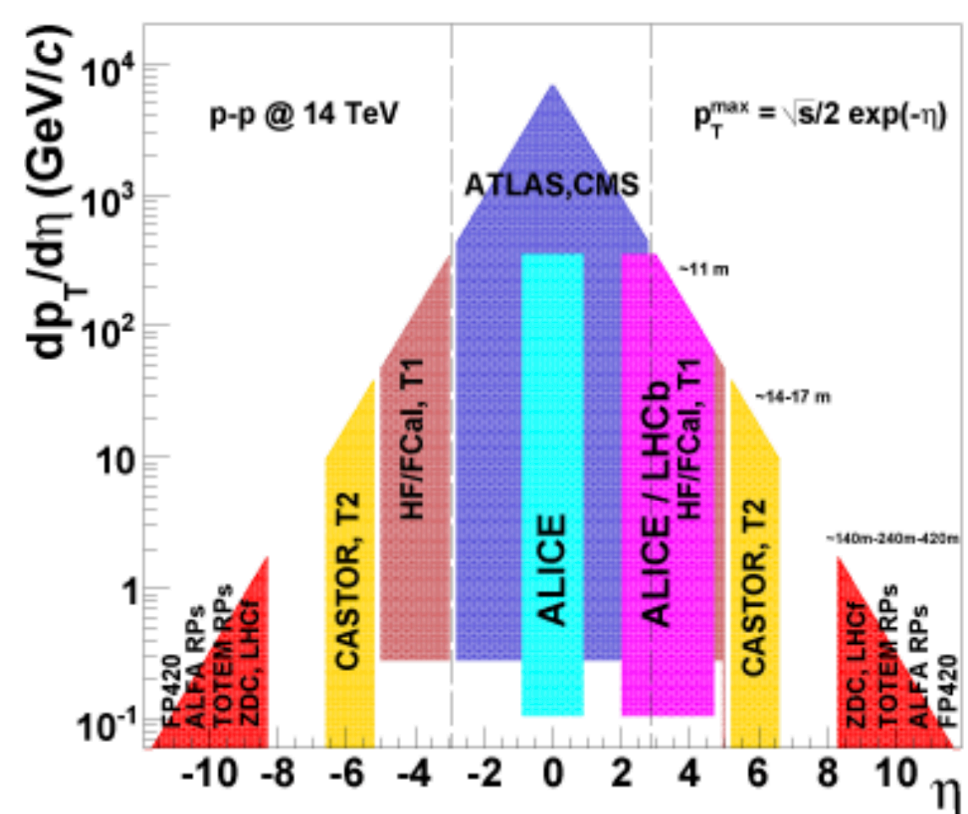
neglecting mass effects

$$y \simeq \eta = \log \tan(\theta/2)$$

scattering angle

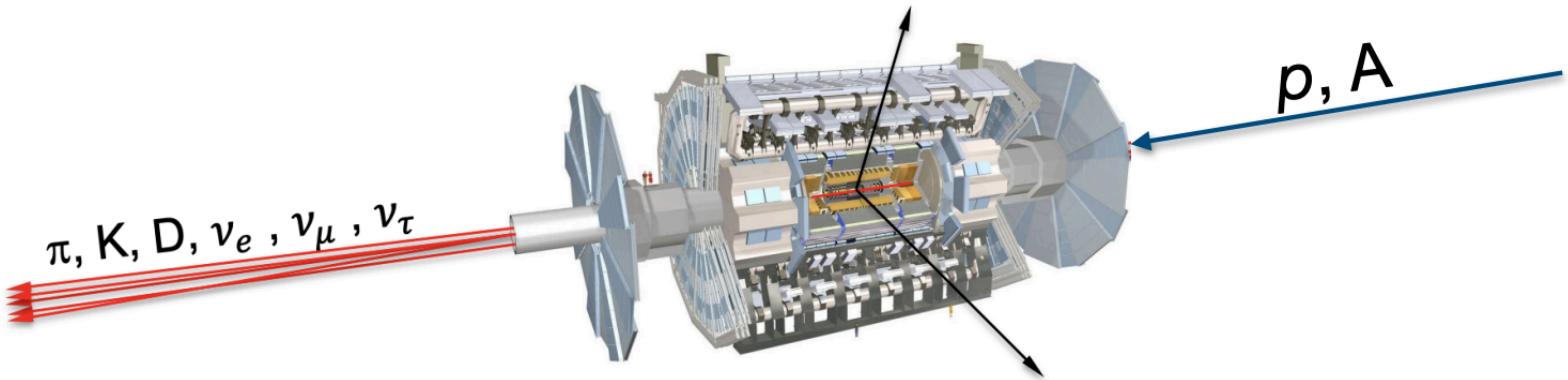
- Forward region for hard-scattering physics restricted to **LHCb** ($\eta < 4.5$) and in the future **ALICE-FoCal** ($\eta < 5.0$)

- **Far-forward region** essentially beyond access for current LHC detectors, except for *e.g.* total cross-section analyses



The LHC as a neutrino factory

- LHC collisions result into a **large flux of energetic neutrinos** which escape the detectors unobserved: **major blind spot of the LHC**



- Being able to detect and utilise the **most energetic human-made neutrinos ever produced** would open many exciting avenues in QCD, neutrino, and astroparticle physics

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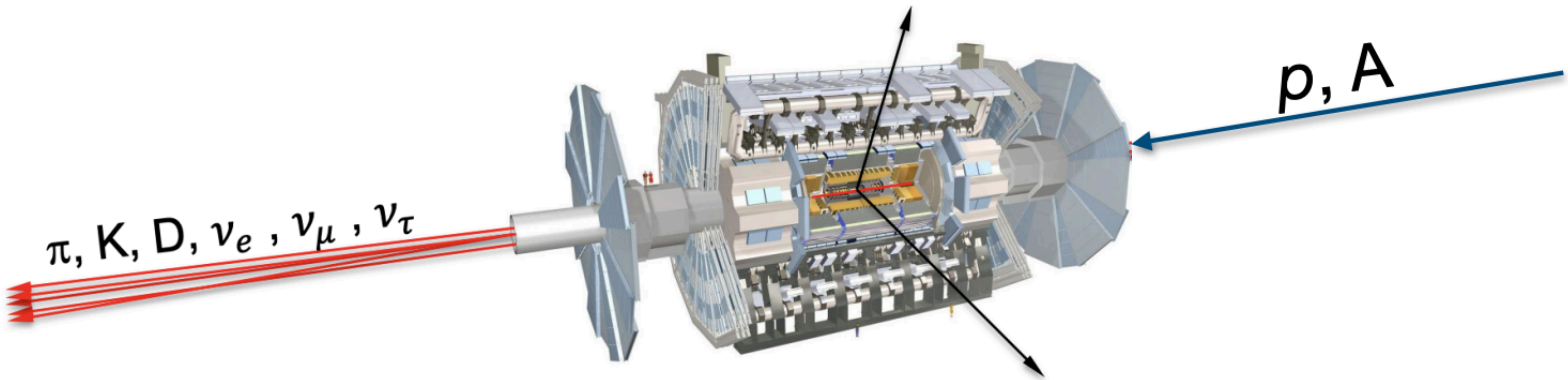

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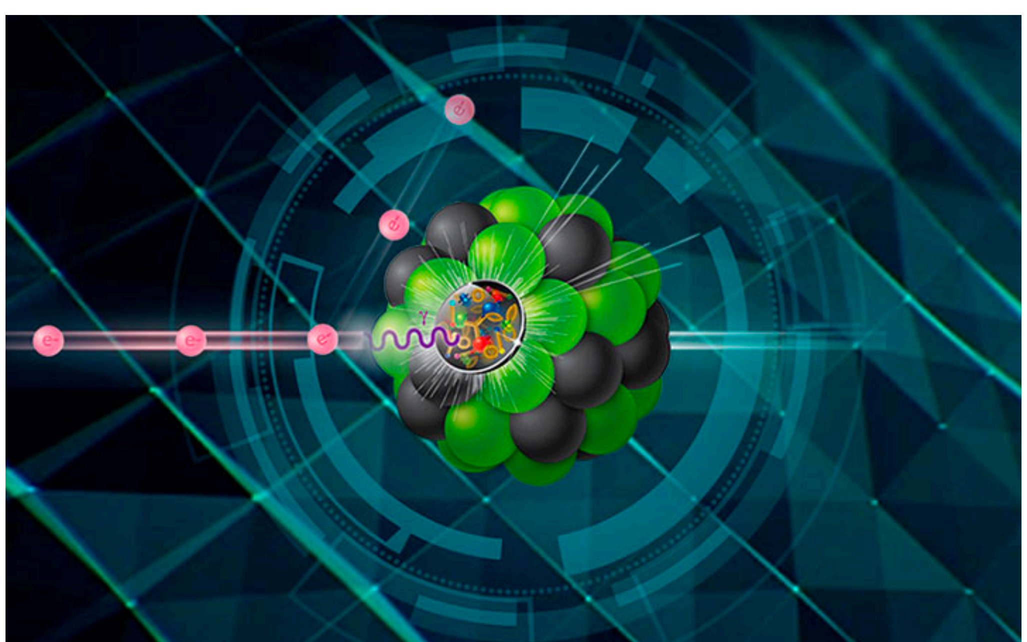
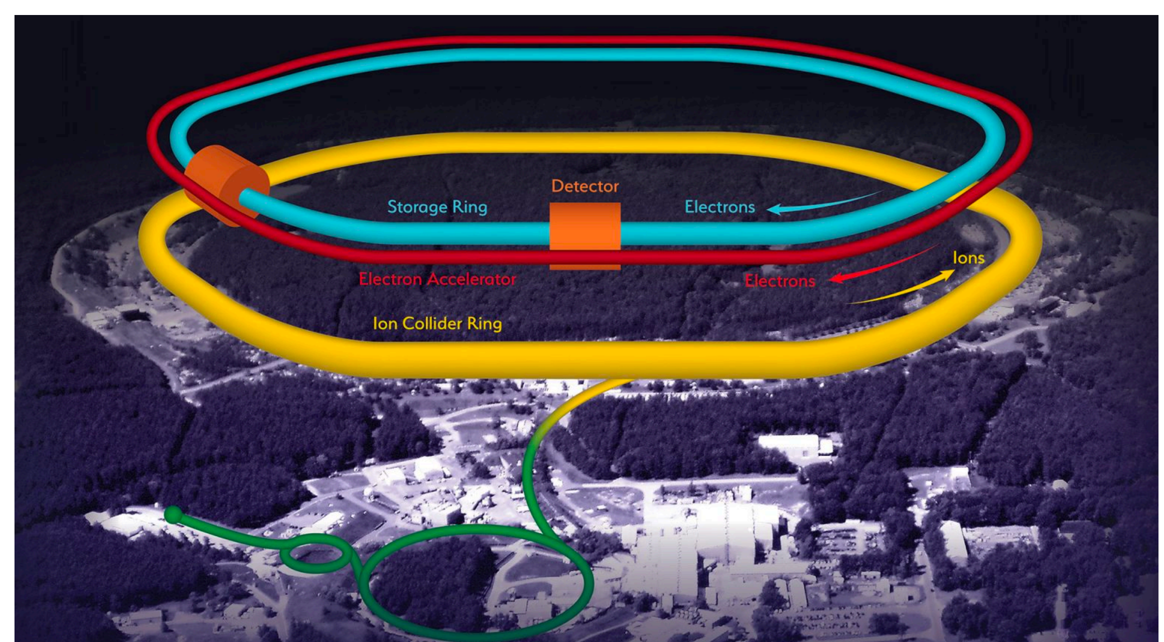
TeV neutrino deep-inelastic scattering: charged-current counterpart of Electron Ion Collider





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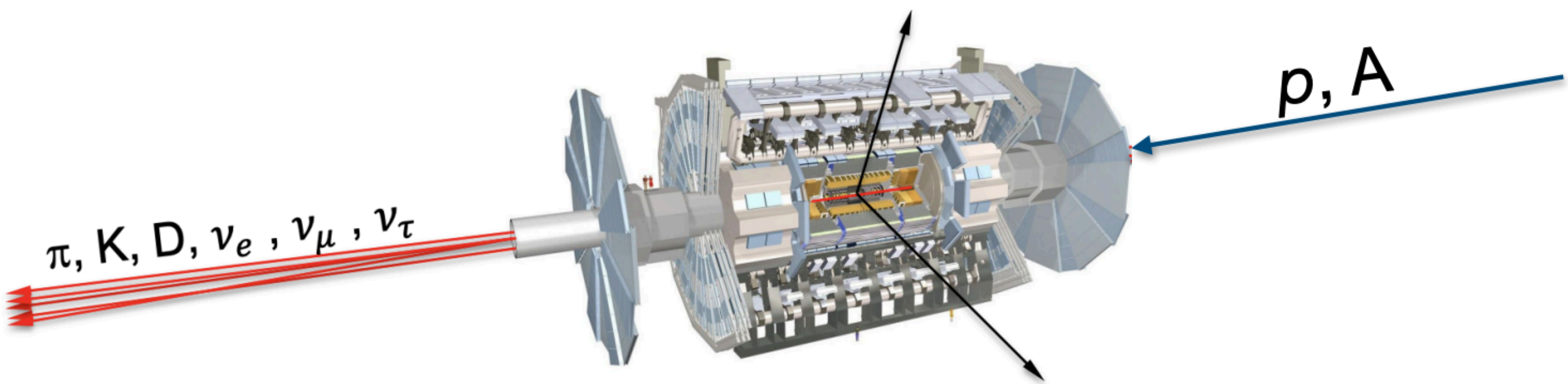

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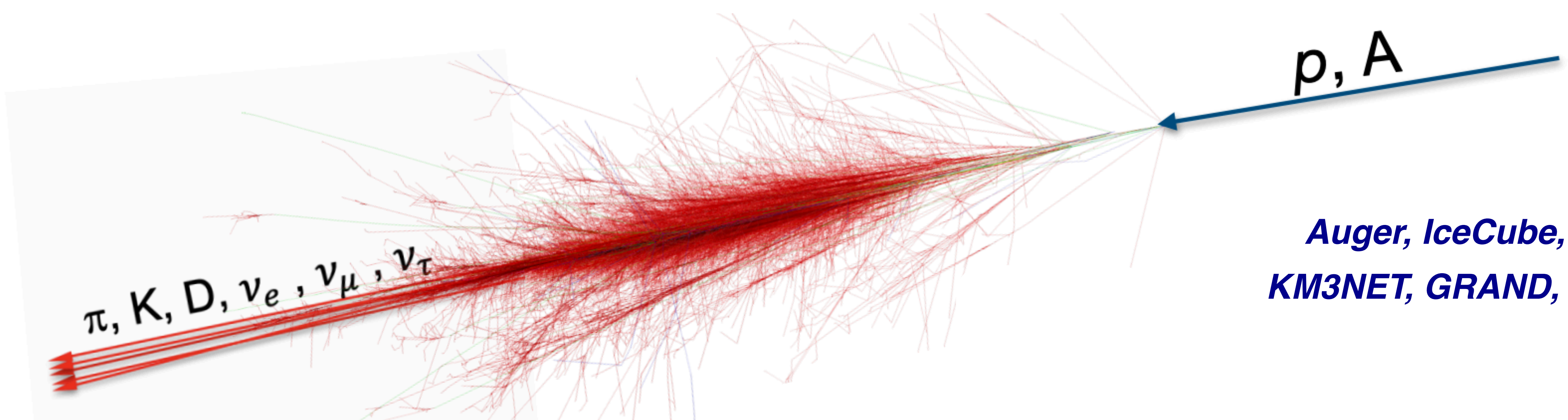
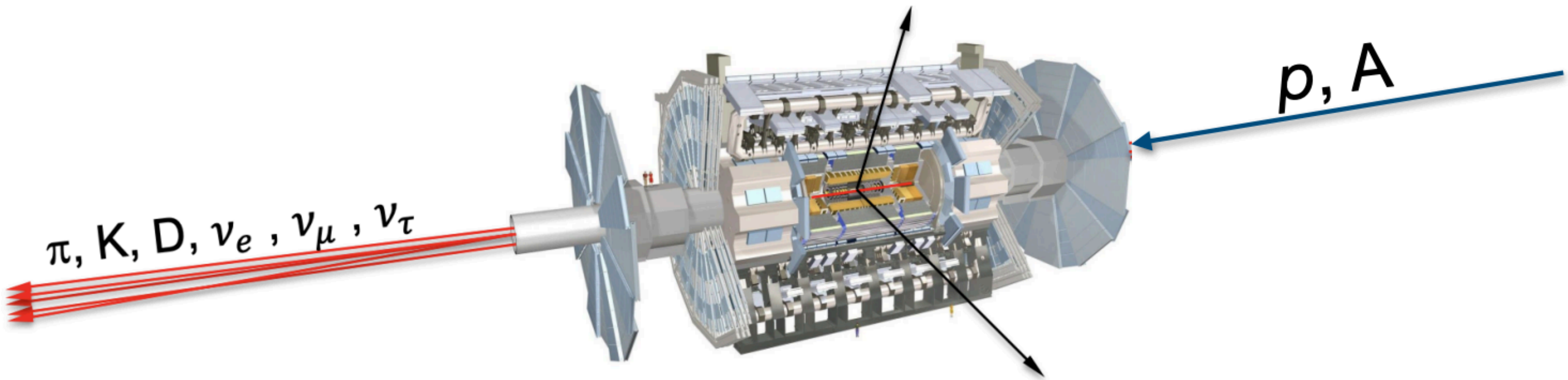
Collider counterpart of high-energy cosmic rays interactions, including prompt neutrino flux



Auger, IceCube, KM3NET, GRAND, …

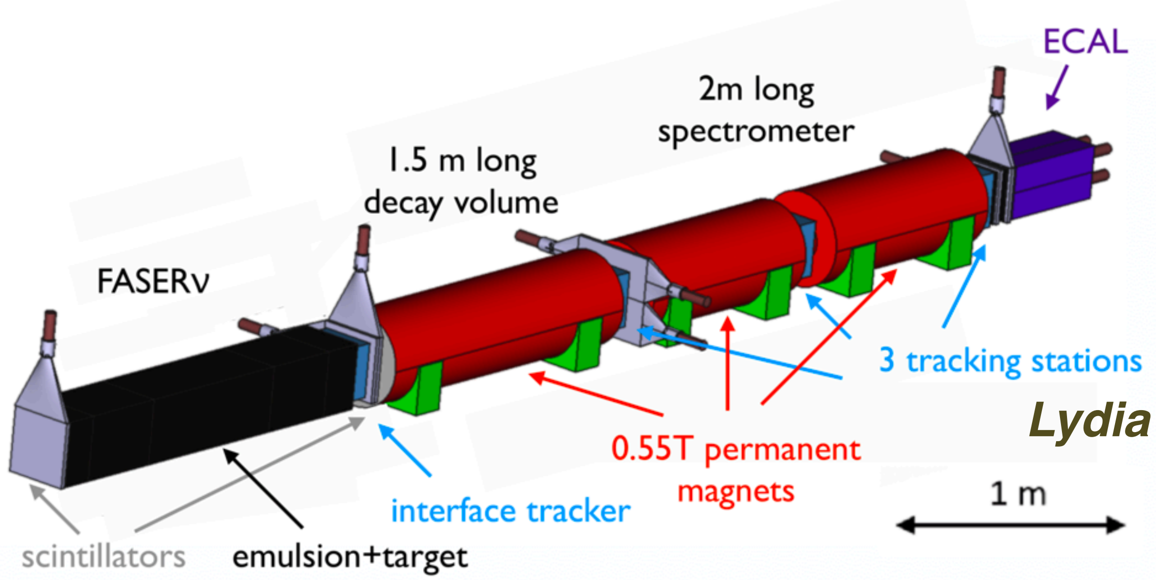
The LHC as a neutrino factory

- LHC collisions result into a **large flux of energetic neutrinos** which escape the detectors unobserved: **major blind spot of the LHC**



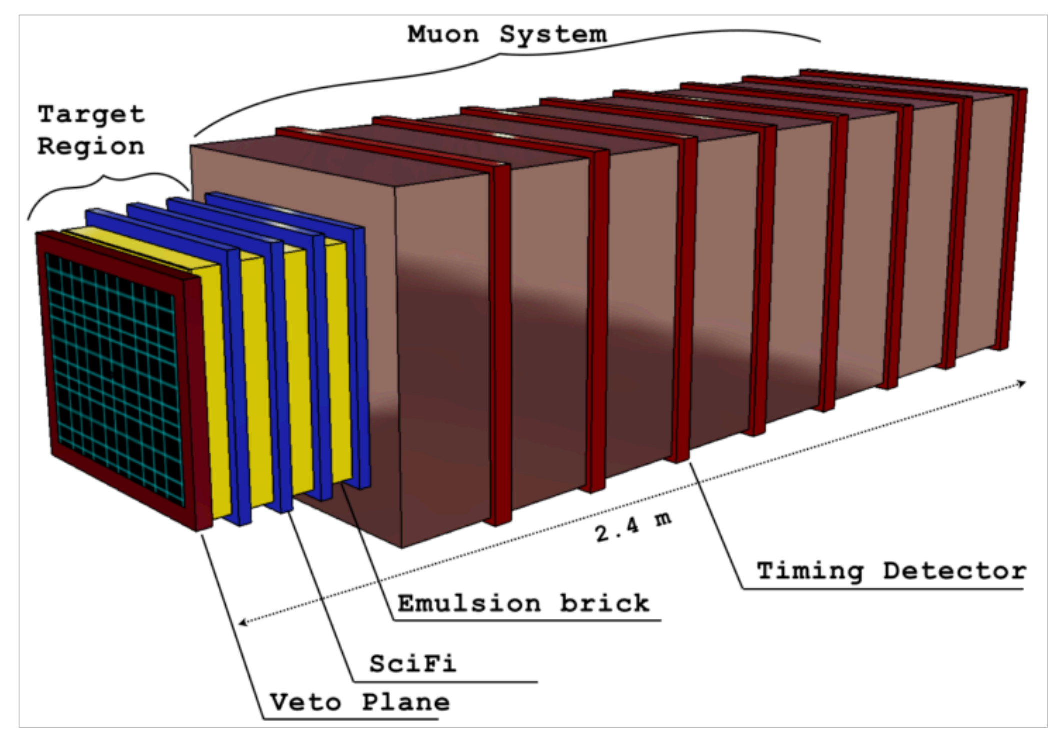
- Being able to detect and utilise the **most energetic human-made neutrinos ever produced** would open many exciting avenues in QCD, neutrino, and astroparticle physics

the feasibility of neutrino physics at the LHC already demonstrated by FaserNu and SND@LHC experiments



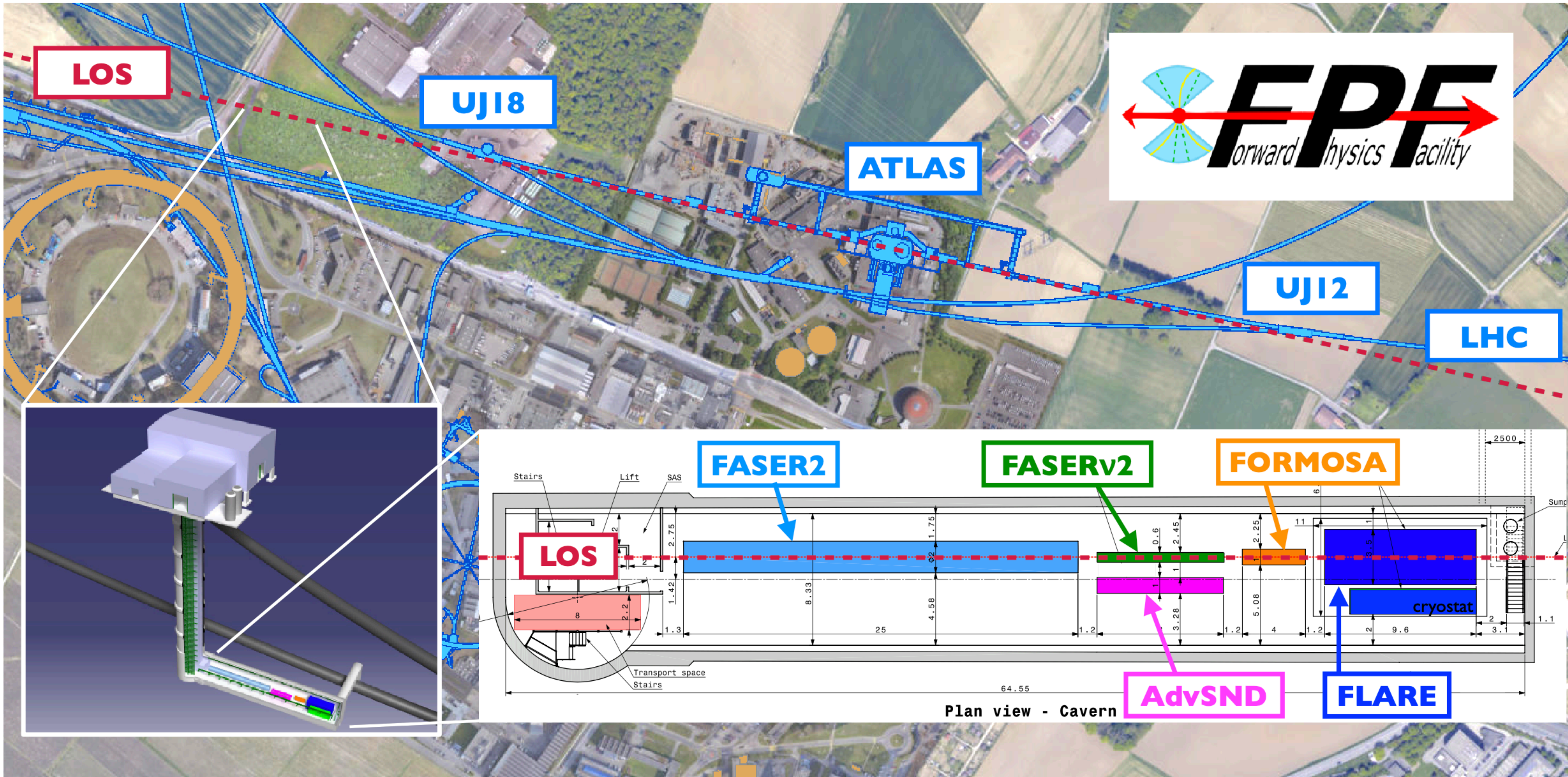
Lydia's talk!

2021: first neutrino detection @ FaserNu



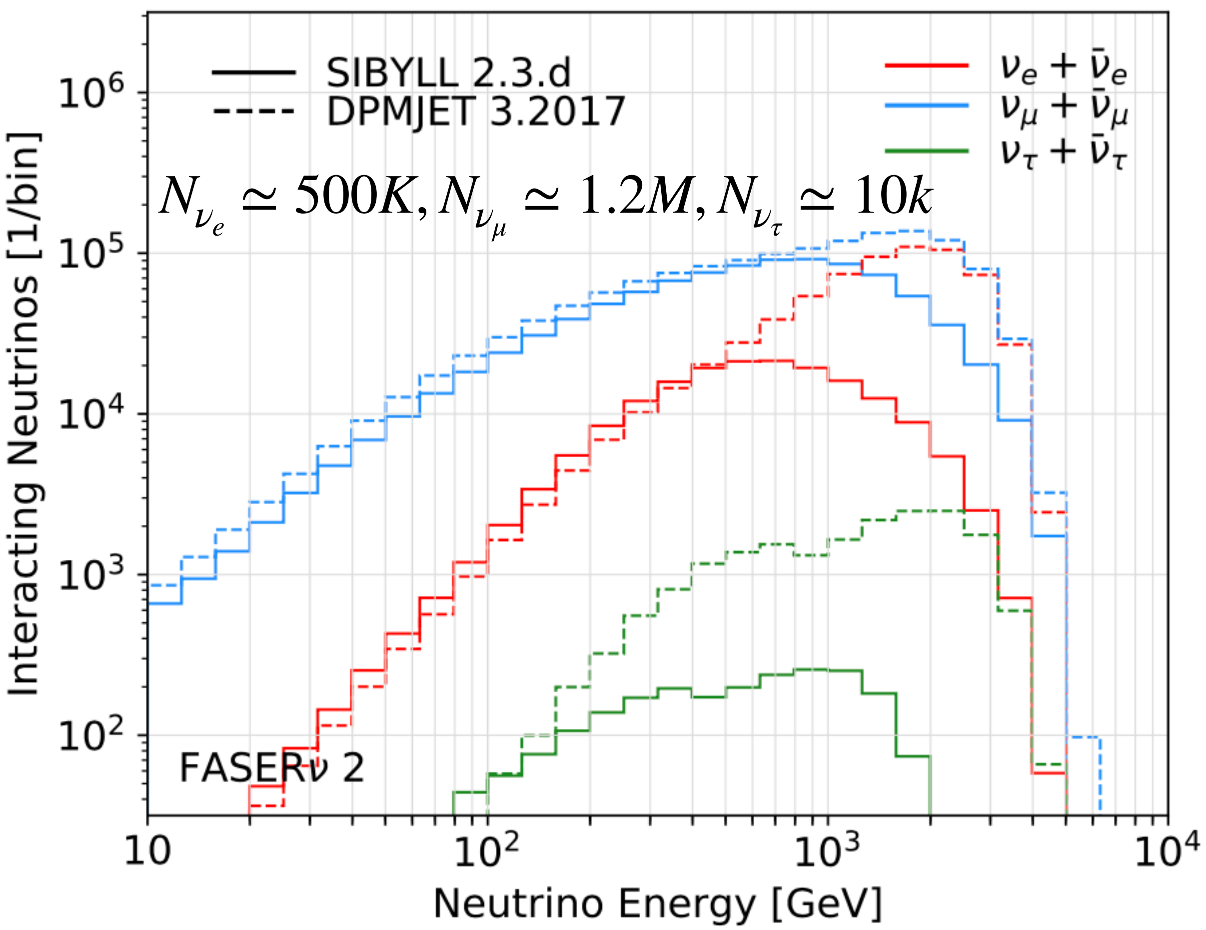
The Forward Physics Facility

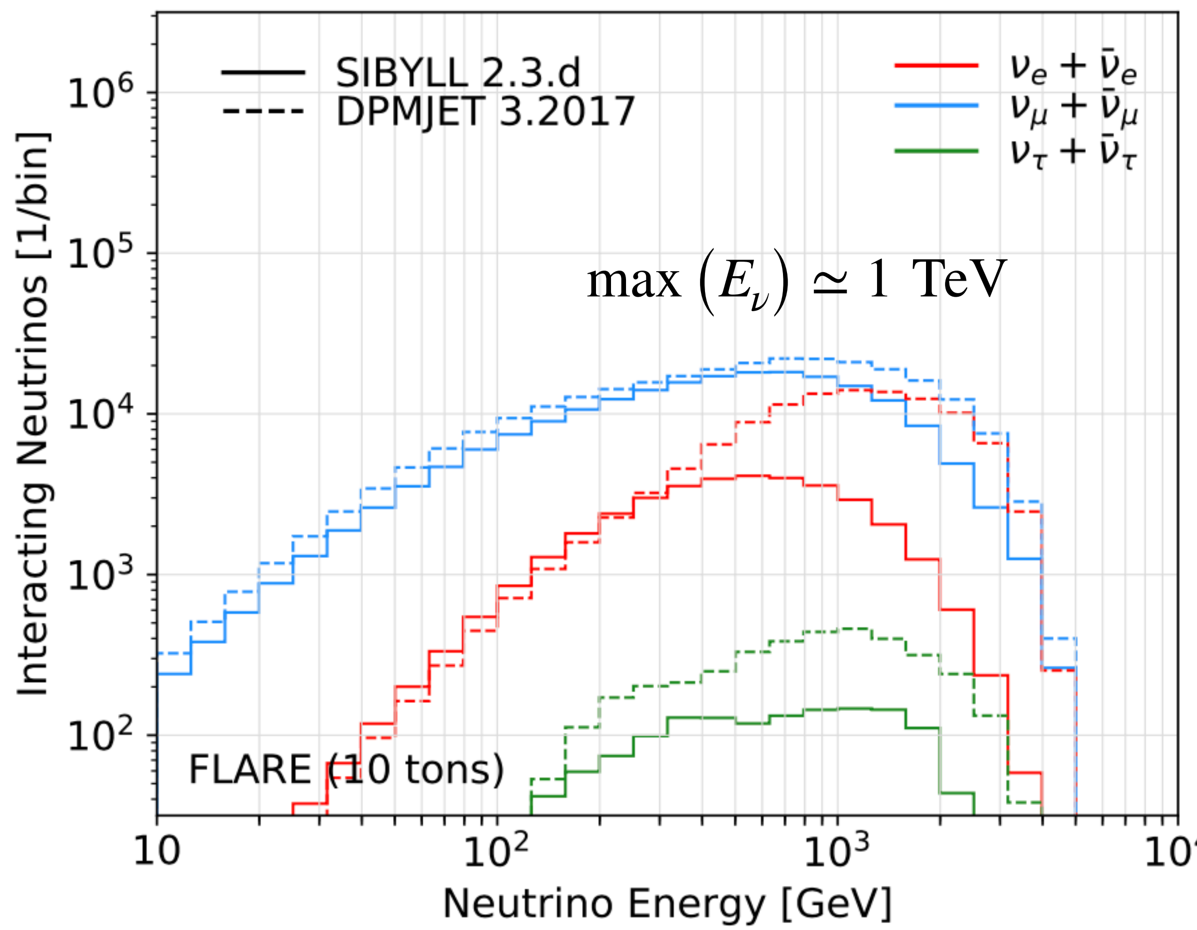
A new facility in a tailor-made underground cavern hosting a suite of **far-forward experiments** suitable to detect **long-lived BSM particles** and **neutrinos** produced at the HL-LHC

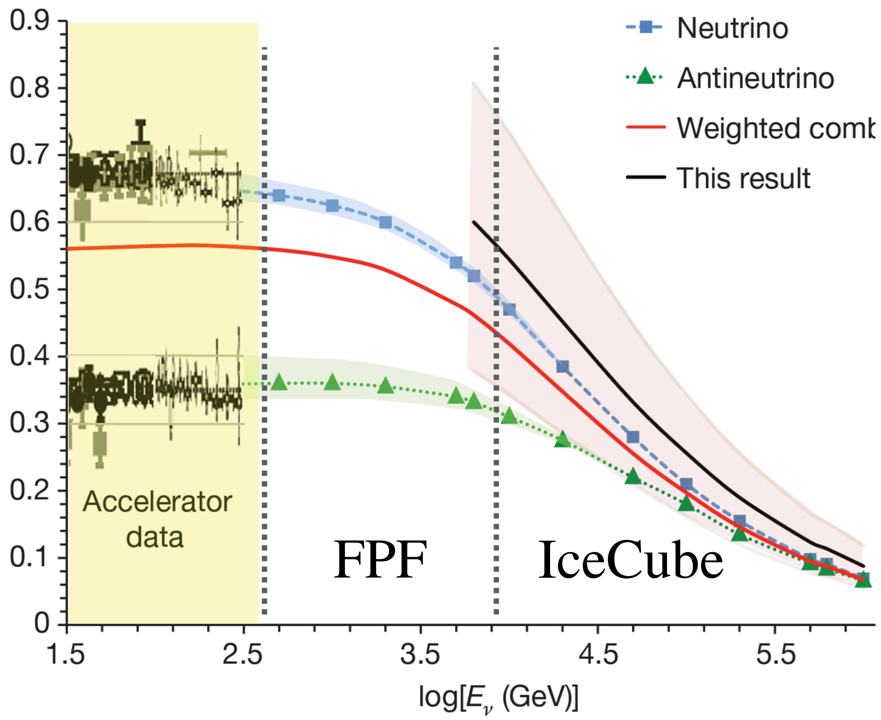


no modifications to the HL-LHC infrastructure or operations required

The Forward Physics Facility







Detector				Number of CC Interactions		
Name	Mass	Coverage	Luminosity	$\nu_e+\bar{\nu}_e$	$\nu_\mu+\bar{\nu}_\mu$	$\nu_\tau+\bar{\nu}_\tau$
FASERν	1 ton	$\eta \gtrsim 8.5$	150 fb^{-1}	901 / 3.4k	4.7k / 7.1k	15 / 97
SND@LHC	800kg	$7 < \eta < 8.5$	150 fb^{-1}	137 / 395	790 / 1.0k	7.6 / 18.6
FASERν2	20 tons	$\eta \gtrsim 8.5$	3 ab^{-1}	178k / 668k	943k / 1.4M	2.3k / 20k
FLArE	10 tons	$\eta \gtrsim 7.5$	3 ab^{-1}	36k / 113k	203k / 268k	1.5k / 4k
AdvSND	2 tons	$7.2 \lesssim \eta \lesssim 9.2$	3 ab^{-1}	6.5k / 20k	41k / 53k	190 / 754

Large events rates: precision measurements of neutrino interactions

unique sensitive to TeV neutrino scattering

FPF physics potential

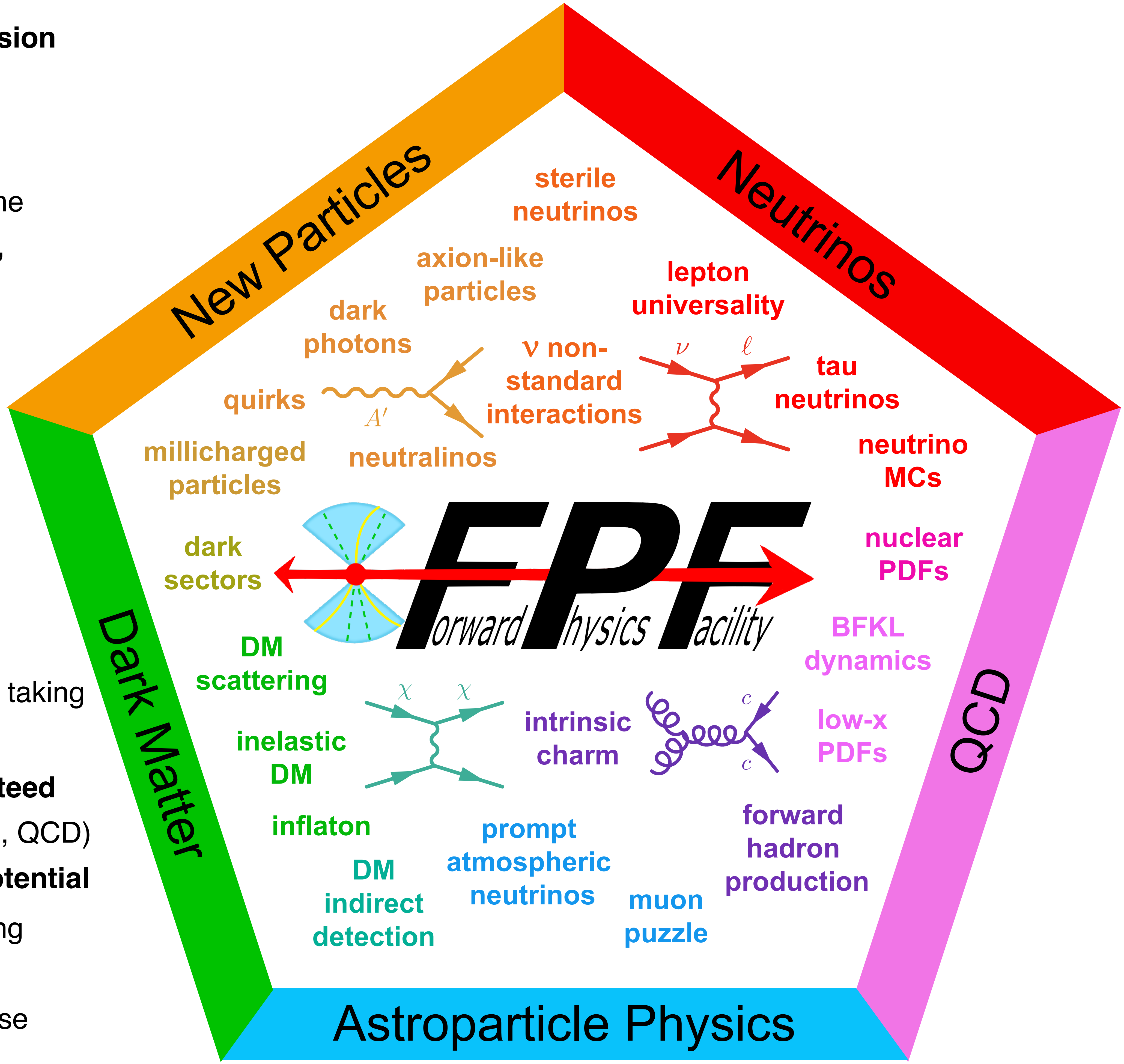
broad and **far-reaching potential** of the FPF experiments:

- BSM searches
  - **Light BSM particles** produced in the very forward direction
  - Decaying **dark sector long-lived particles** (dark photons, dark Higgs, heavy neutral leptons…)
  - Milli-charged particles, dark matter scattering, …

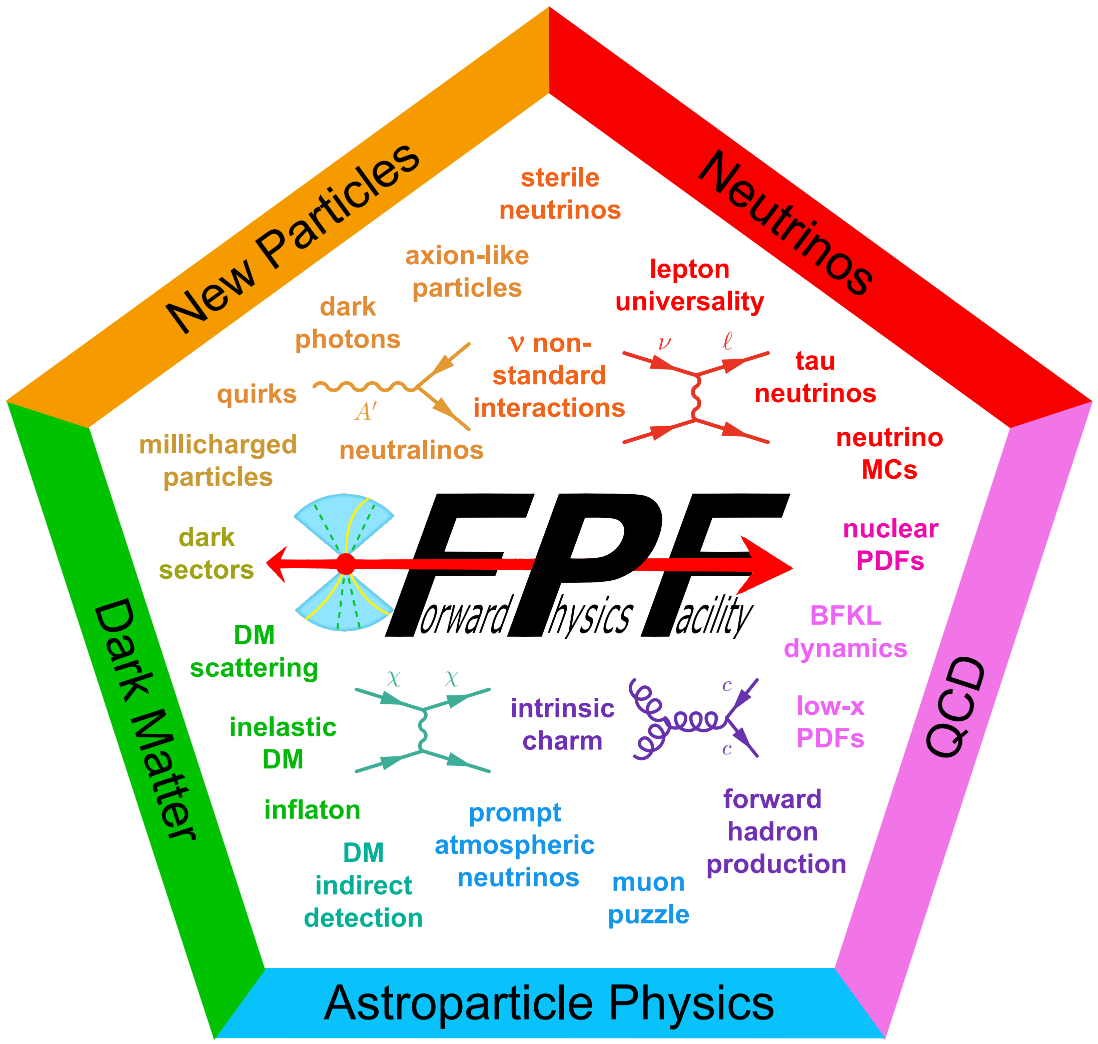
- Neutrino physics
  - **Tau neutrino** studies (10k tau neutrino interactions, current world sample <20)
  - Separation of tau neutrino / anti-neutrino, constrain tau neutrino EDM
  - Tau neutrino decays into heavy flavour (connection with **LHCb LFV anomalies**)
  - **EFT constraints** on neutrino interactions

- QCD, hadron structure, and astroparticle physics
  - **Neutrino cross section** measurements (energy region not covered by any other experiment)
  - Neutrino DIS to constrain **proton and nuclear structure**
  - Testing **BFKL dynamics** in LHC collisions, modelling charm, hadron production in forward region
  - Key input for neutrino (IceCube, KM3NET) and cosmic ray **astroparticle experiments**

- Unprecedented **extension of HL-LHC scientific potential**
- Deep synergies with the **Electron Ion Collider, cosmic rays, UHE neutrinos**



- Installation in **LS3**, data taking from **Run 4** onwards
- Combination of **guaranteed deliverables** (neutrinos, QCD) and **BSM discovery potential**
- Updated HL-LHC running schedule **until 2040s** strengthens the FPF case



- **430 pages** describing scientific case, infrastructure, detectors, and simulations
- Stepping stone for the FPF **Conceptual Design Report**

The Forward Physics Facility at the High-Luminosity LHC

High energy collisions at the High-Luminosity Large Hadron Collider (LHC) produce a large number of particles along the beam collision axis, outside of the acceptance of existing LHC experiments. The proposed Forward Physics Facility (FPF), to be located several hundred meters from the ATLAS interaction point and shielded by concrete and rock, will host a suite of experiments to probe Standard Model (SM) processes and search for physics beyond the Standard Model (BSM). In this report, we review the status of the civil engineering plans and the experiments to explore the diverse physics signals that can be uniquely probed in the forward region. FPF experiments will be sensitive to a broad range of BSM physics through searches for new particle scattering or decay signatures and deviations from SM expectations in high statistics analyses with TeV neutrinos in this low-background environment. High statistics neutrino detection will also provide valuable data for fundamental topics in perturbative and non-perturbative QCD and in weak interactions. Experiments at the FPF will enable synergies between forward particle production at the LHC and astroparticle physics to be exploited. We report here on these physics topics, on infrastructure, detector, and simulation studies, and on future directions to realize the FPF's physics potential.

Snowmass Working Groups
EF4,EF5,EF6,EF9,EF10,NF3,NF6,NF8,NF9,NF10,RP6,CF7,TF07,TF09,TF11,AF2,AF5,IF8

Lead Conveners

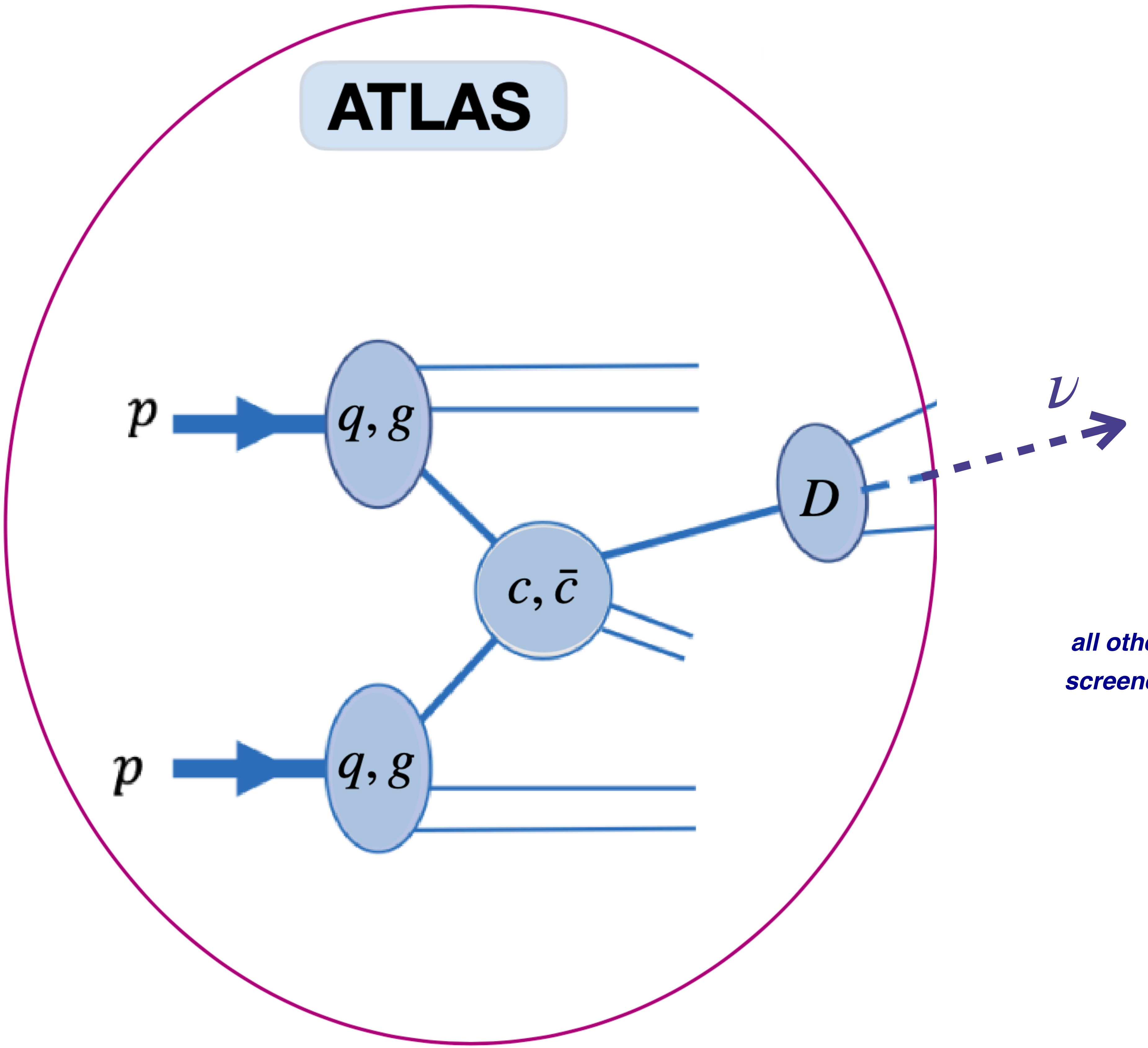
Jonathan L. Feng[1*], Felix Kling[2], Mary Hall Reno[3], Juan Rojo[4,5], Dennis Soldin[6]

Topical Conveners

Luis A. Anchordoqui[7], Jamie Boyd[8], Ahmed Ismail[9], Lucian Harland-Lang[10,11], Kevin J. Kelly[12], Vishvas Pandey[13], Sebastian Trojanowski[14,15], Yu-Dai Tsai[1],

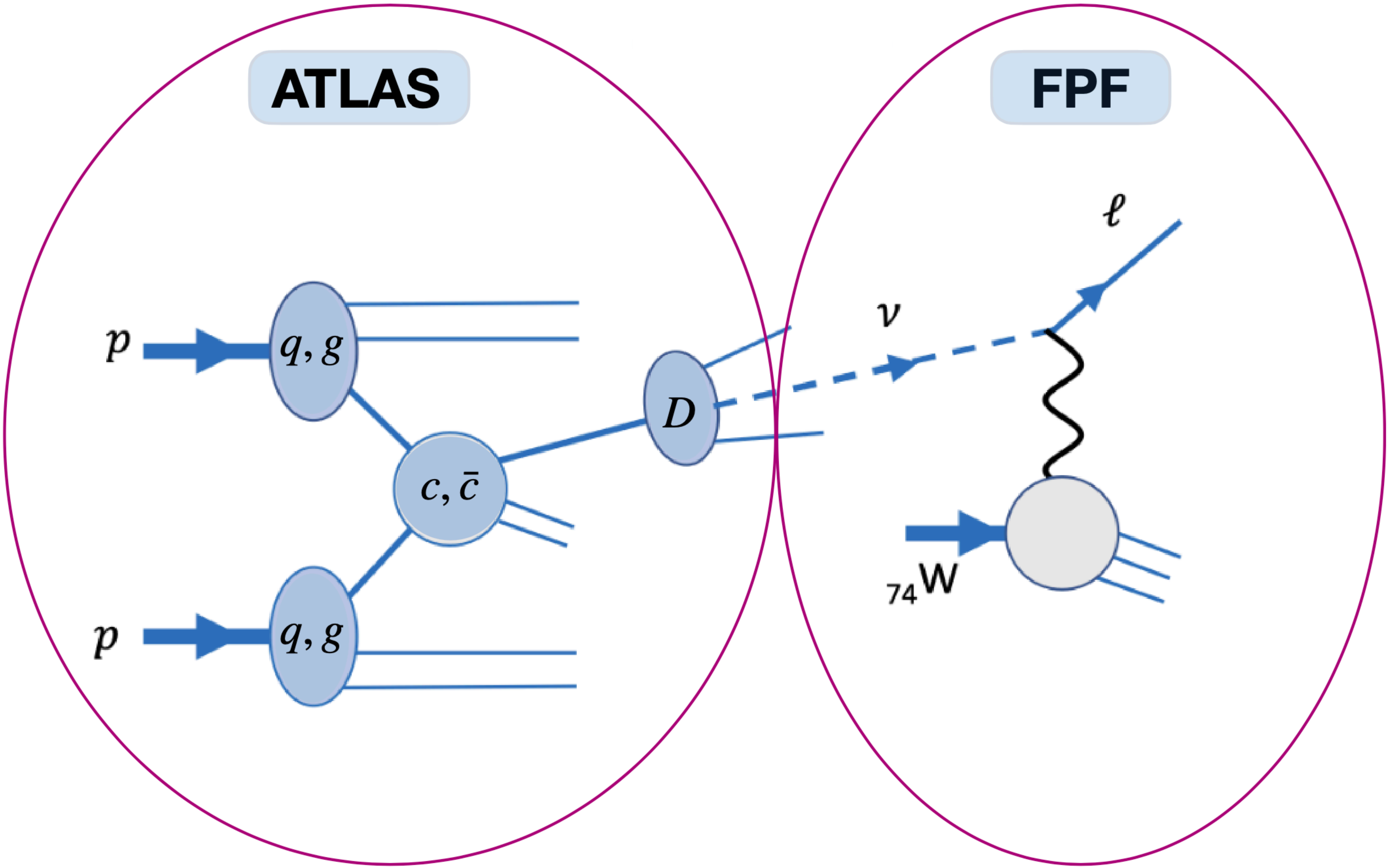
QCD and Neutrino Interactions at the FPF

Neutrino production and detection

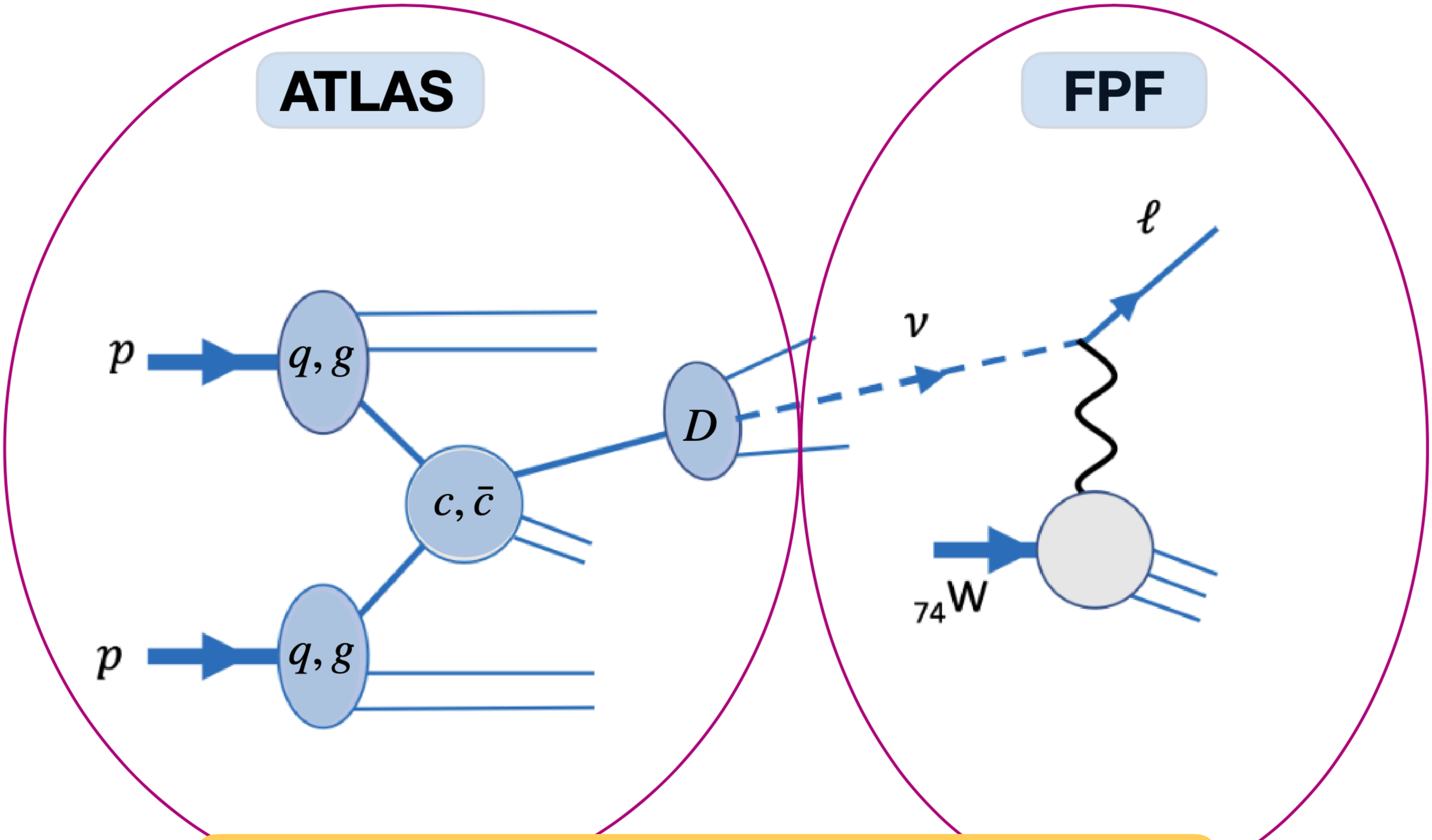


all other SM particles (except muons) screened by 1km of rock and concrete

Neutrino production and detection

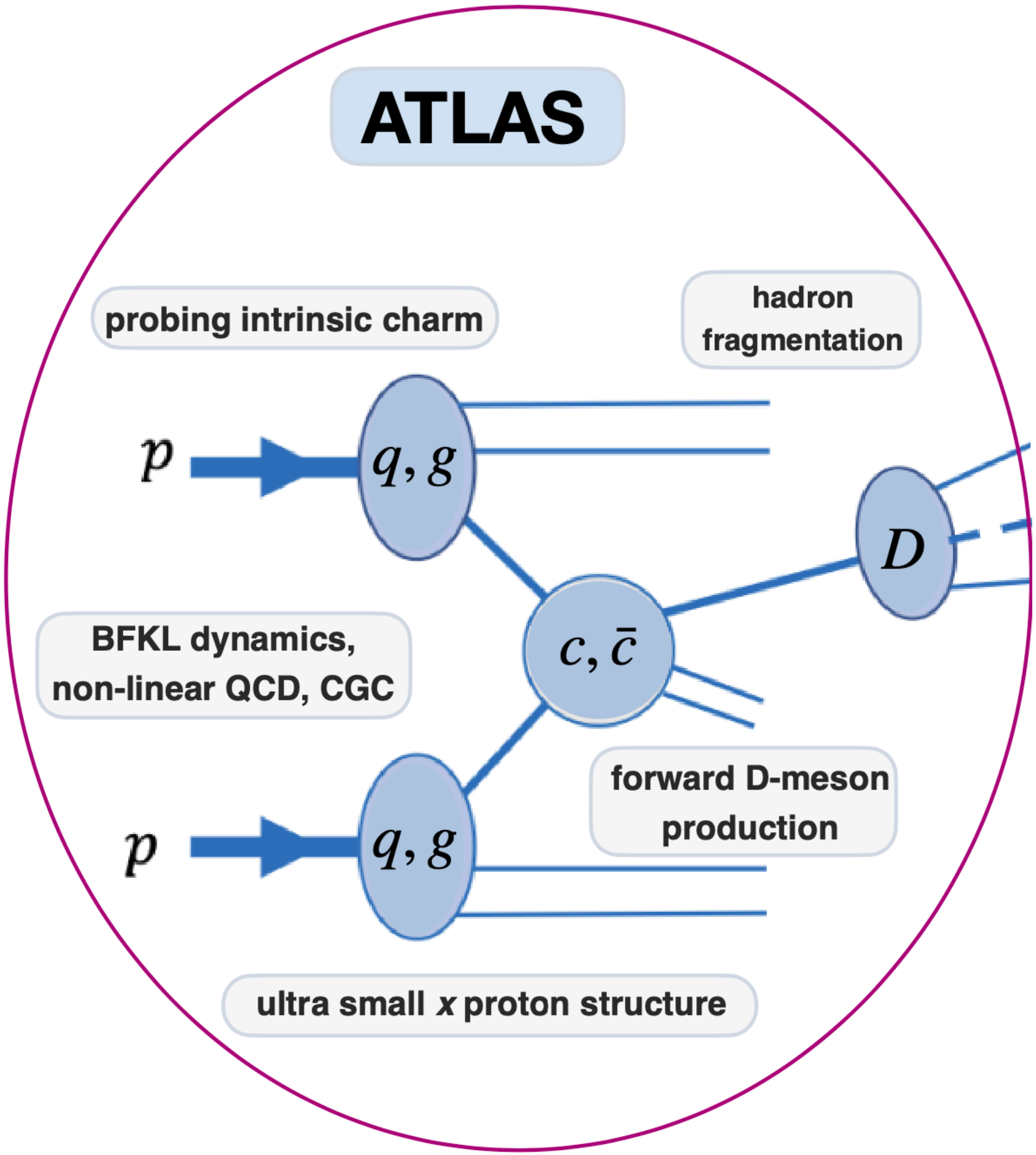


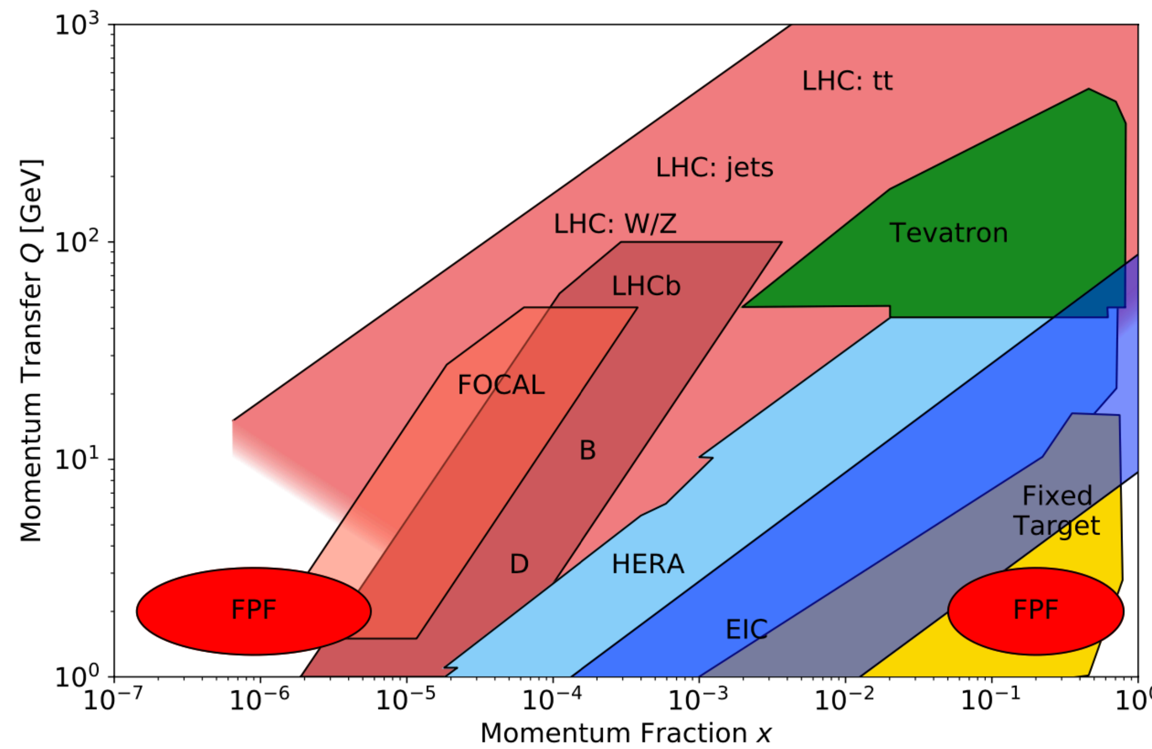
Neutrino production and detection



The FPF is equivalent to a Neutrino-Ion Collider with $E_{CM} \approx 80$ GeV

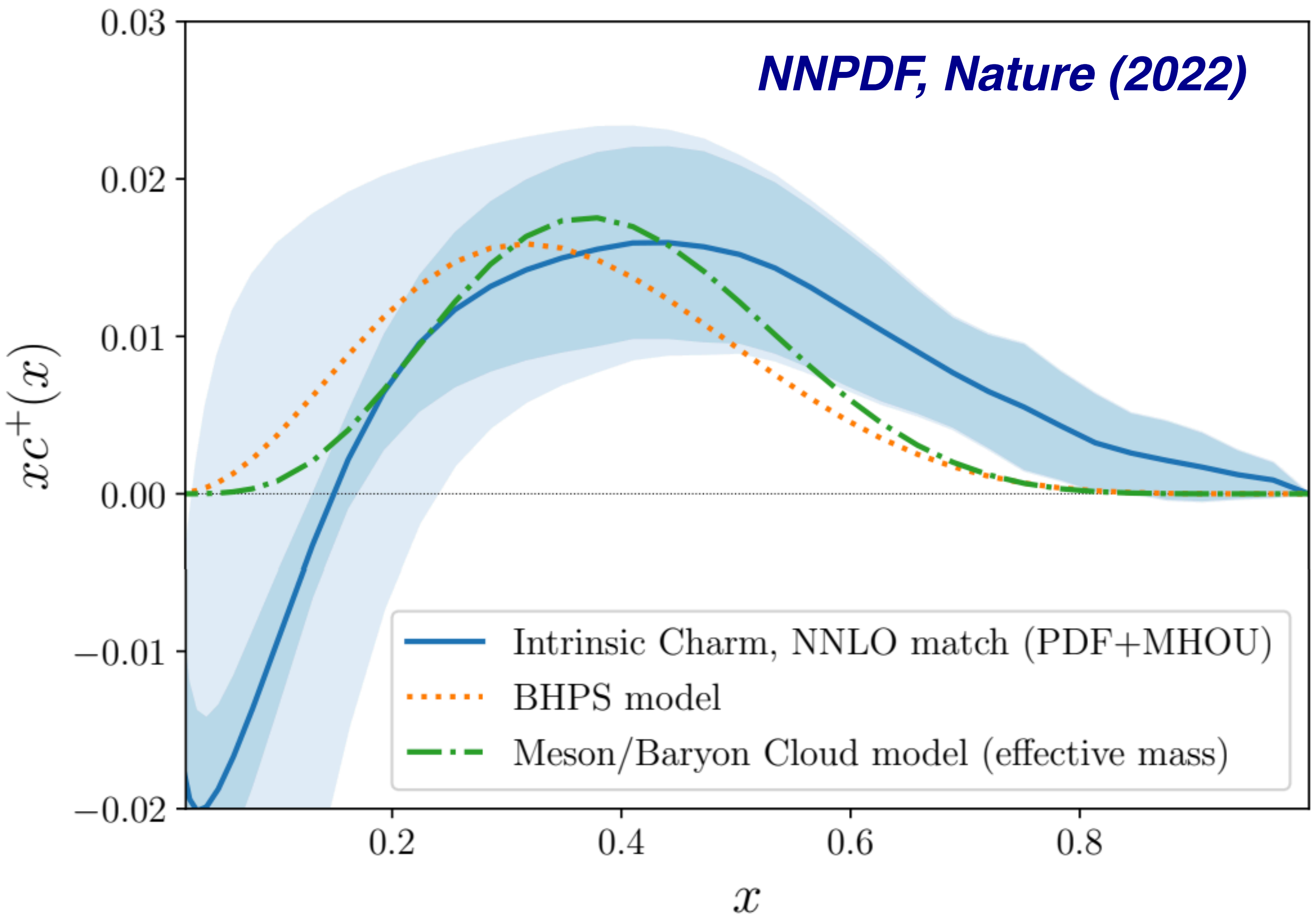
QCD at the FPF

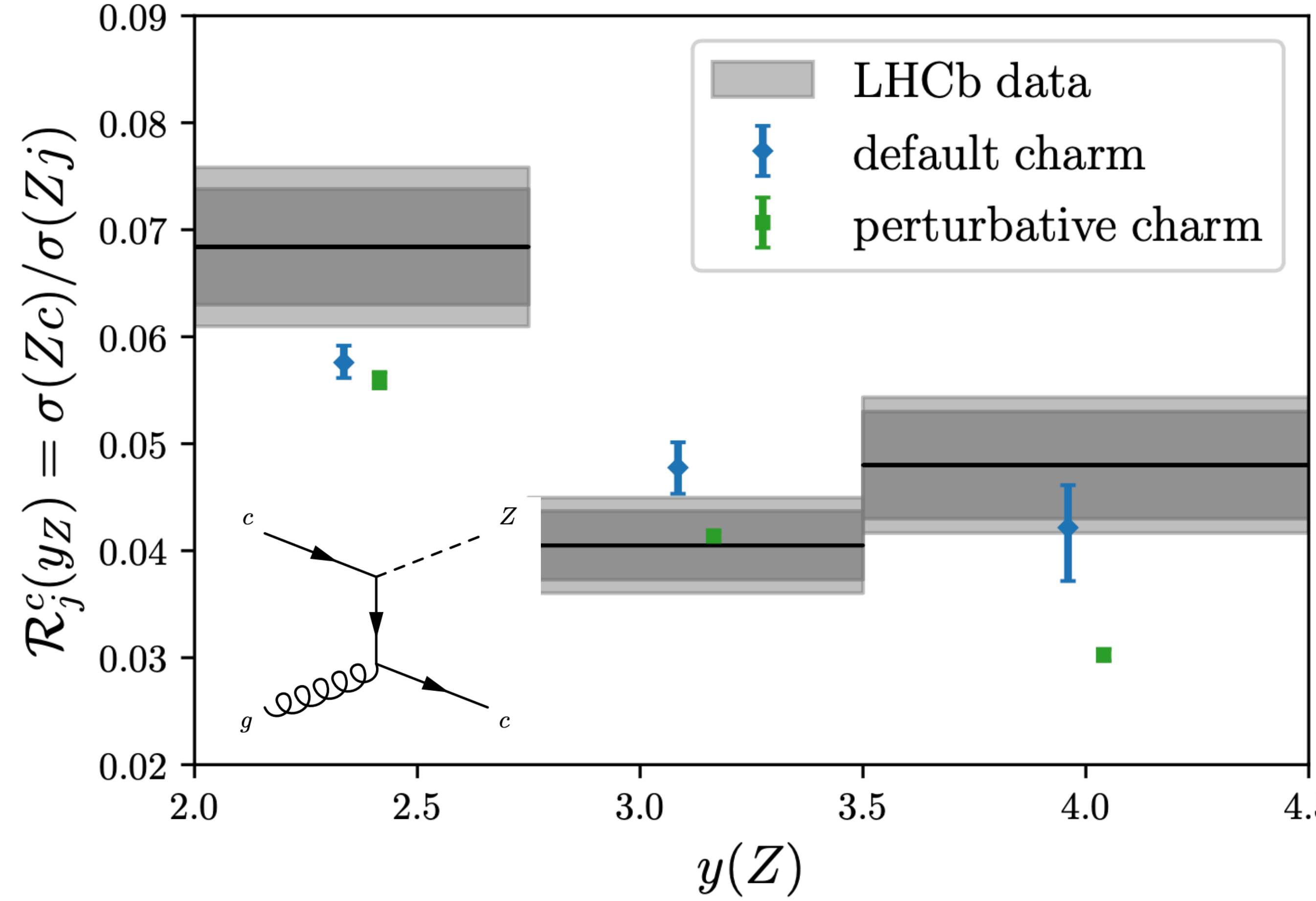


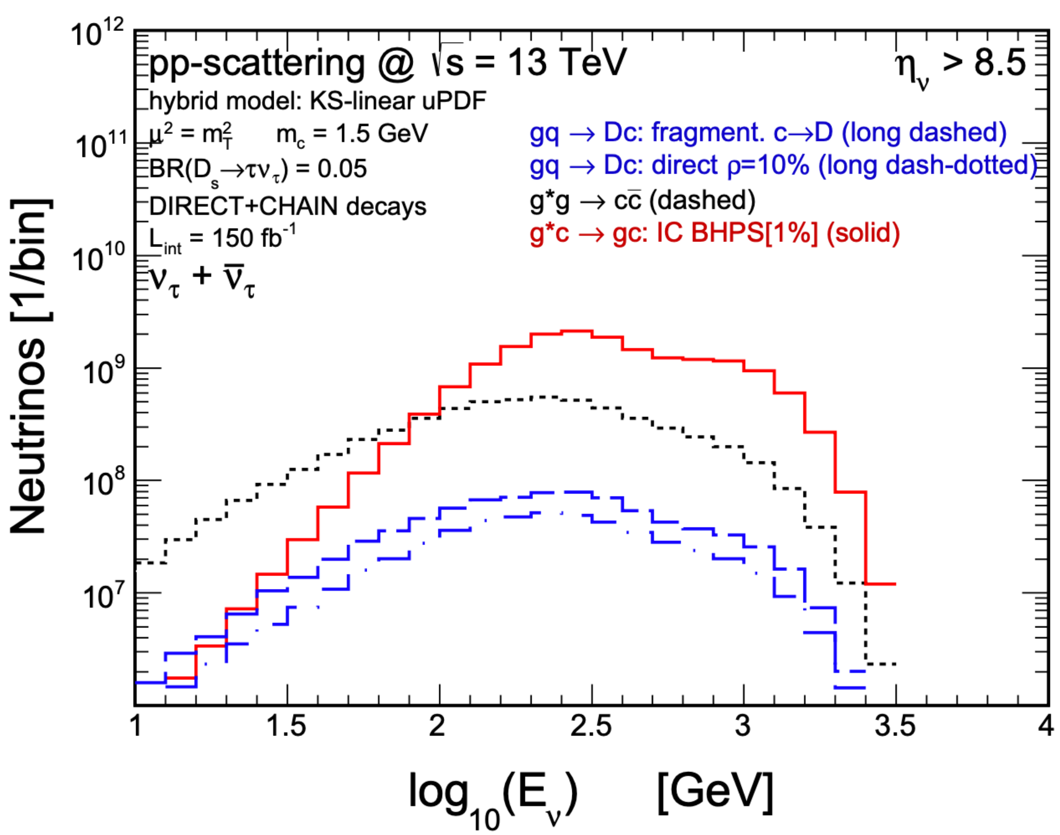


- **Forward particle production** (light hadrons & D-mesons) sensitive down to $\boldsymbol{x=10^{-7}}$
- Ultra small-*x* proton structure & **BFKL / non-linear QCD** dynamics
- Tune models of **forward hadron fragmentation**
- Constraints on **intrinsic charm**

QCD at the FPF

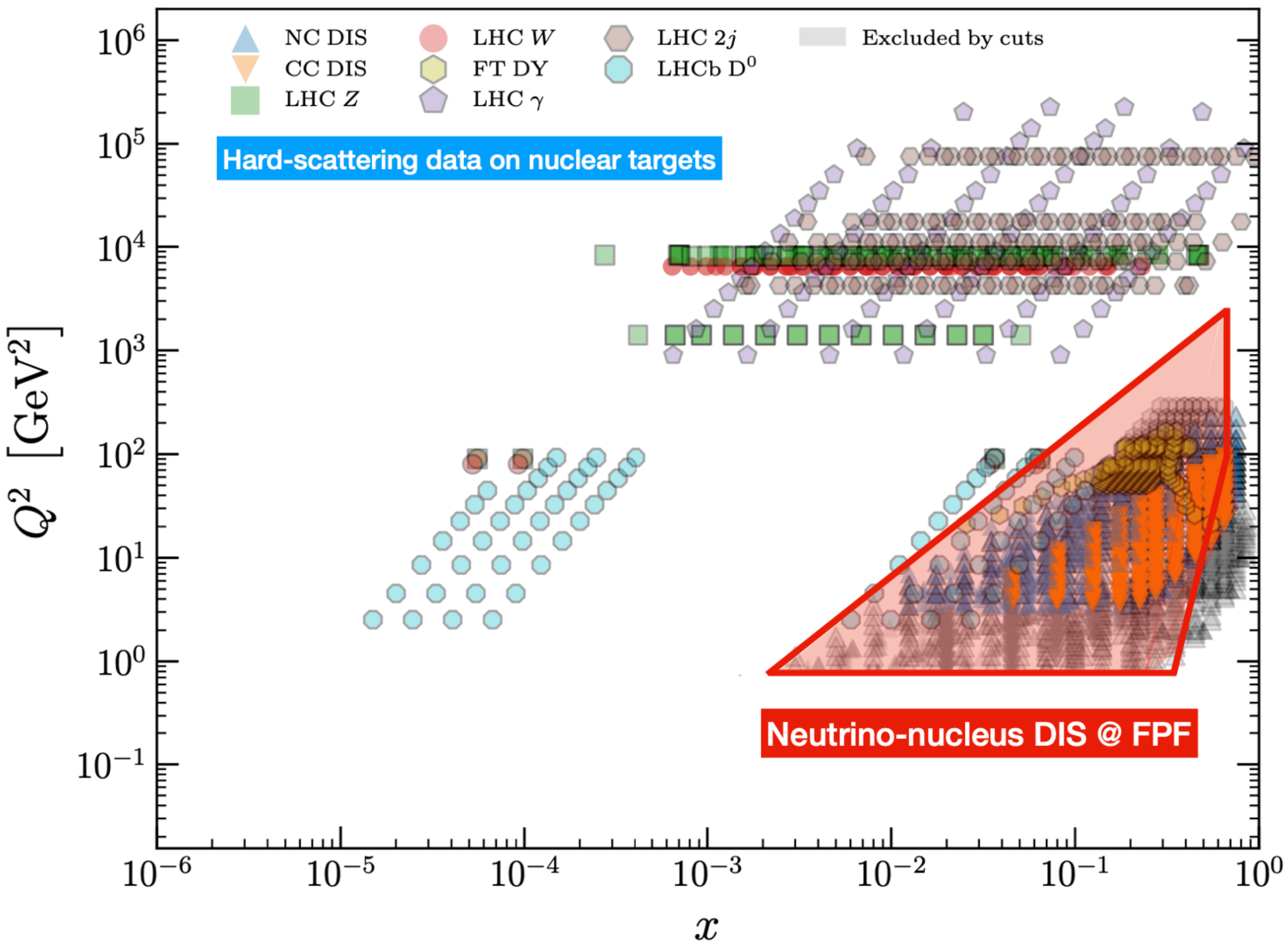




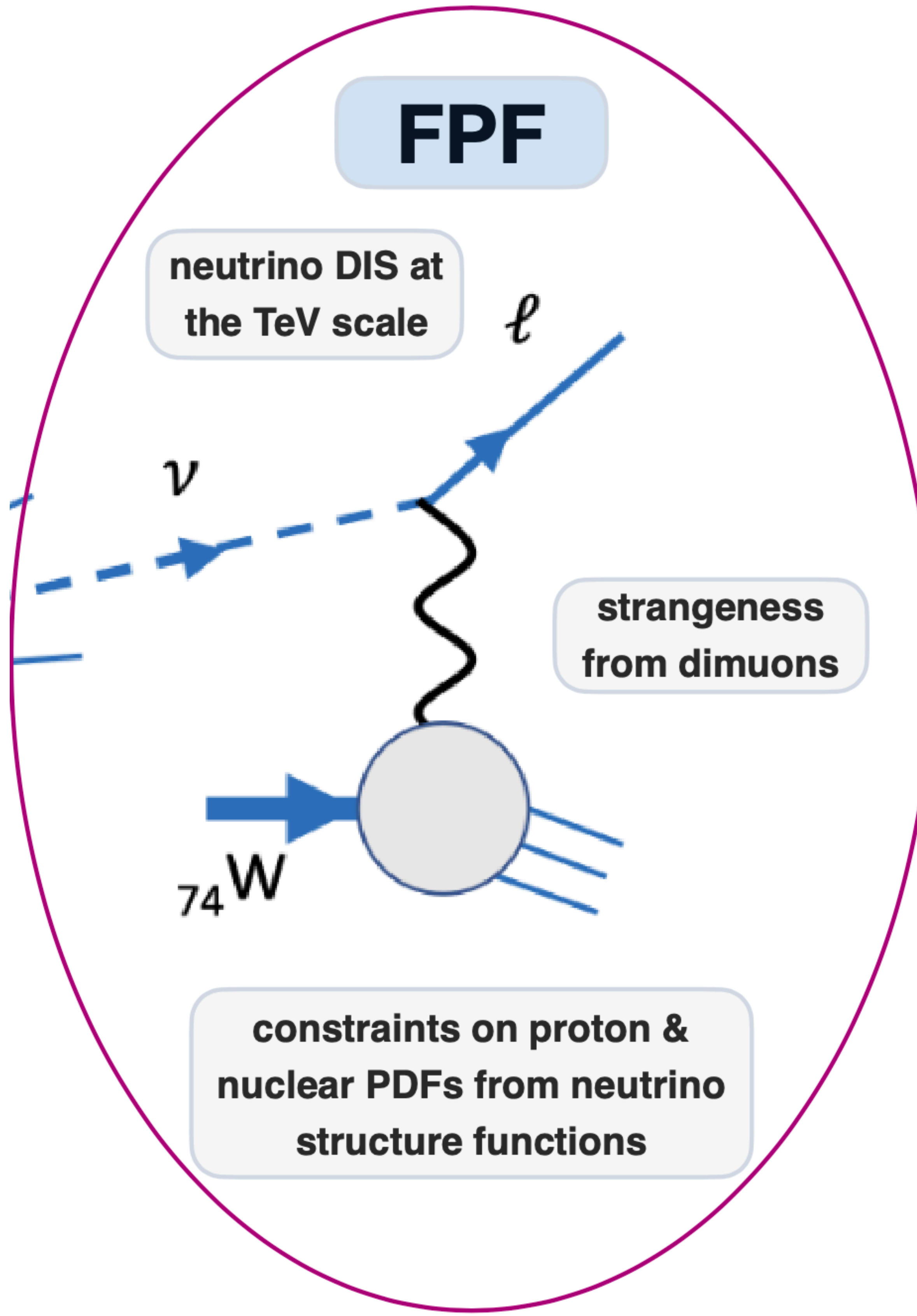


- Recent evidence for **intrinsic charm quarks** in the proton from global QCD analysis, validated by LHCb *Z+c* data
- IC enhances rates for **forward charm production** leading to e.g. factor 3 enhancement in **tau neutrino rates at FPF**
- FPF unique probe of intrinsic heavy quarks, key feedback for **prompt neutrino flux** calculations at IceCube/KM3NET

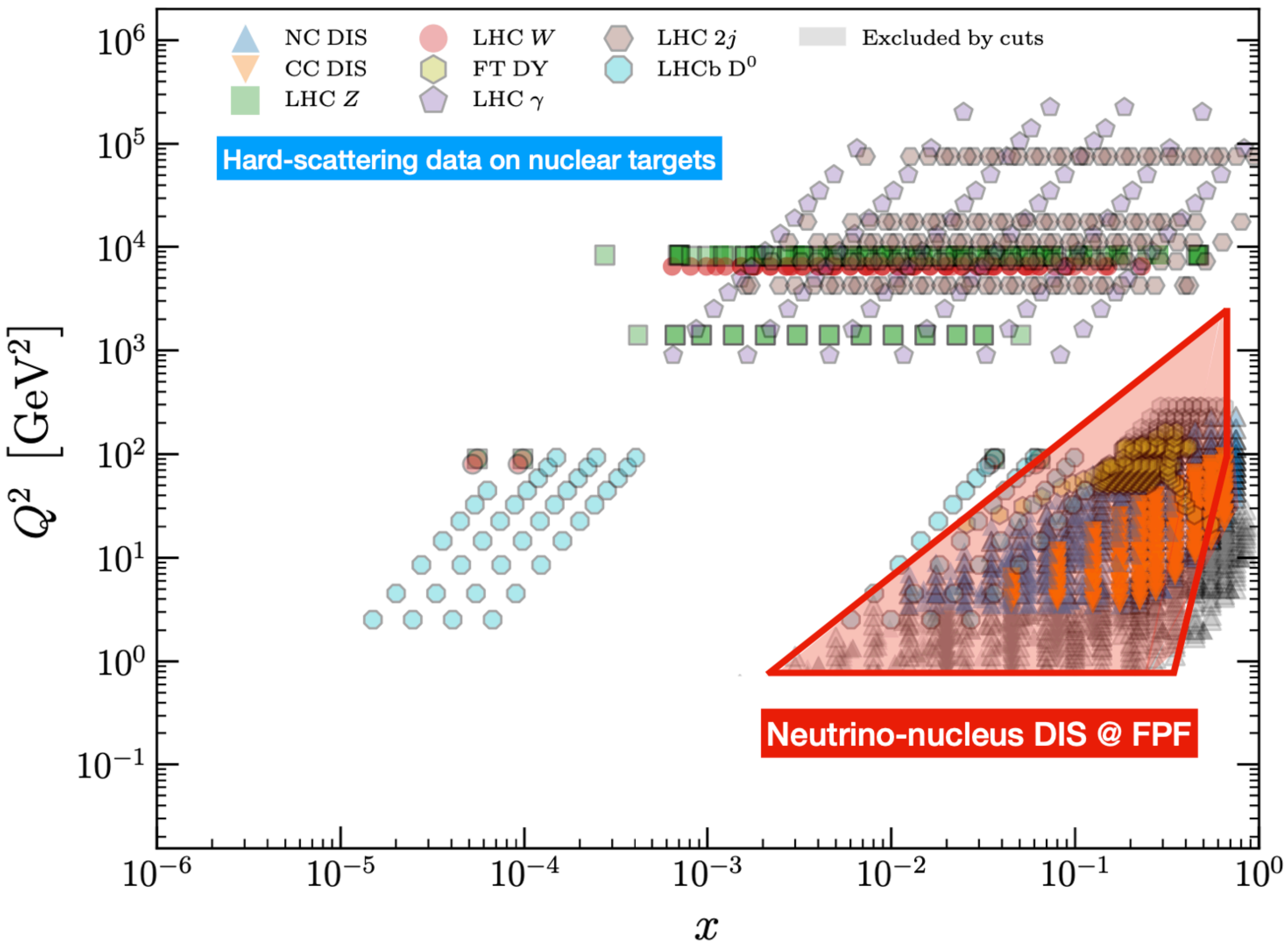
QCD at the FPF

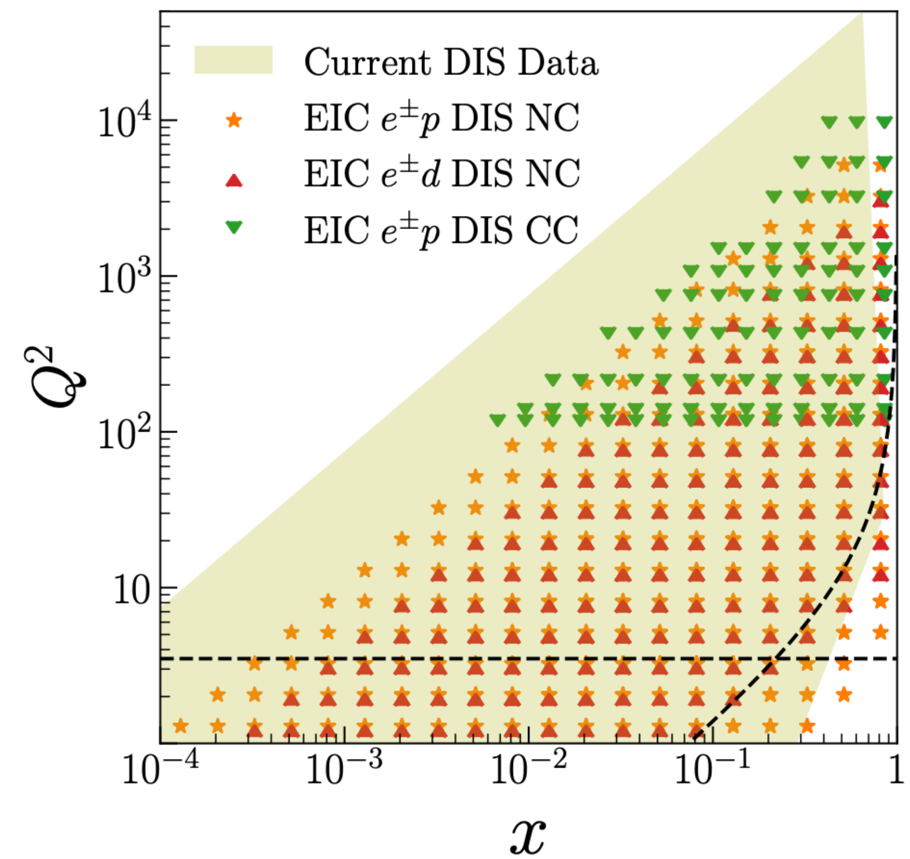


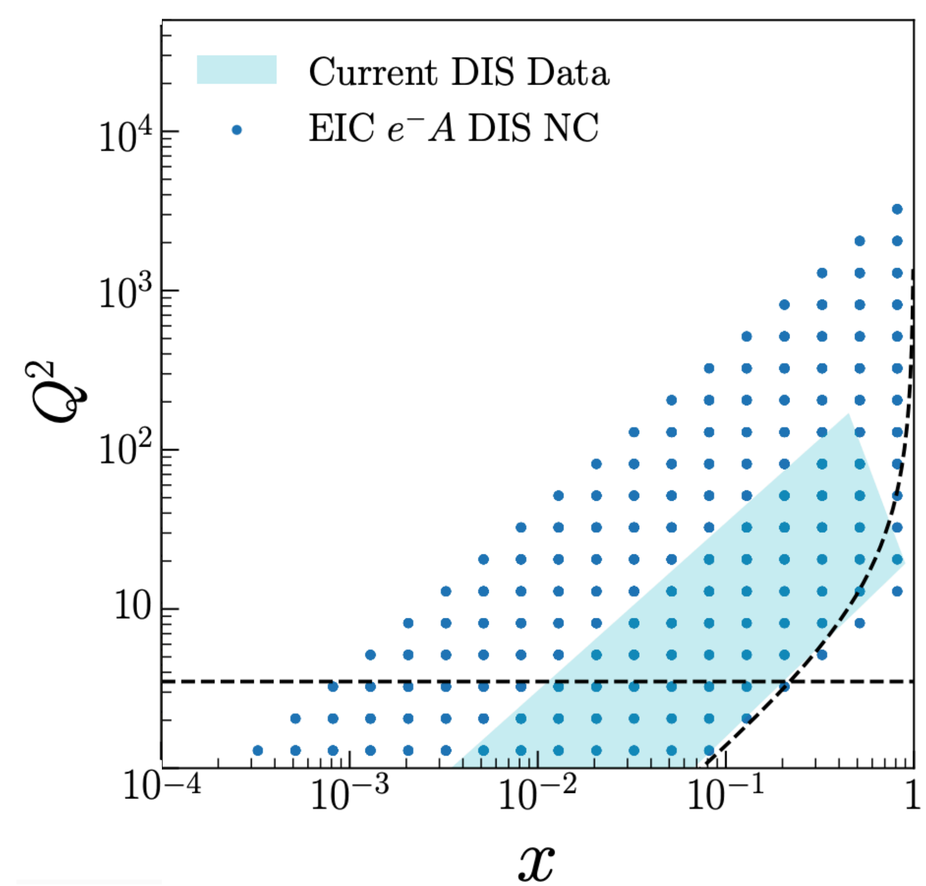
- Deep-inelastic CC scattering with **TeV neutrinos**
- Continue succesful program of neutrino **DIS experiments @ CERN**
- Constrain proton & nuclear **light (anti-)quark PDFs**



QCD at the FPF







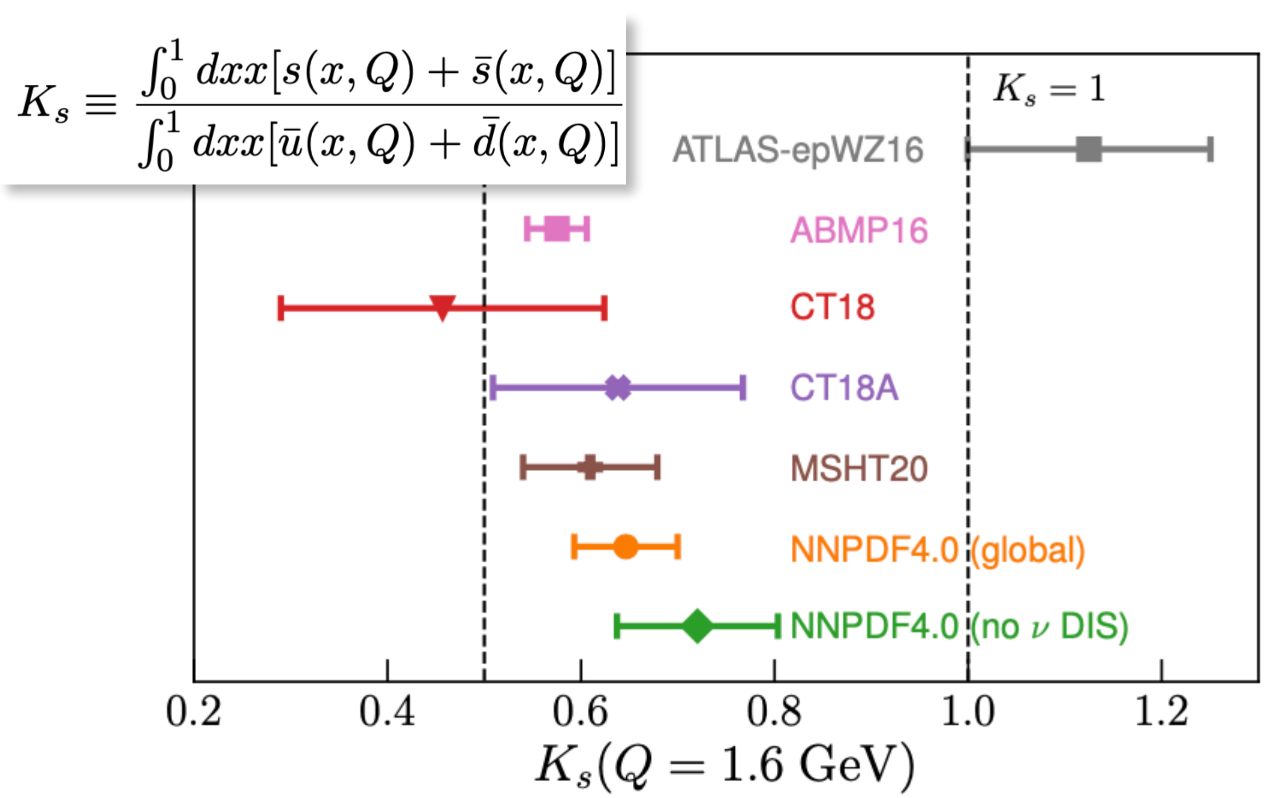
- Excellent complementarity between **EIC (neutral current)** and **FPF (charged current)** measurements of DIS structure function on proton and nuclear targets
- A **joint analysis of EIC+FPF data** markedly improves the (n)PDF reach of **individual experiments**

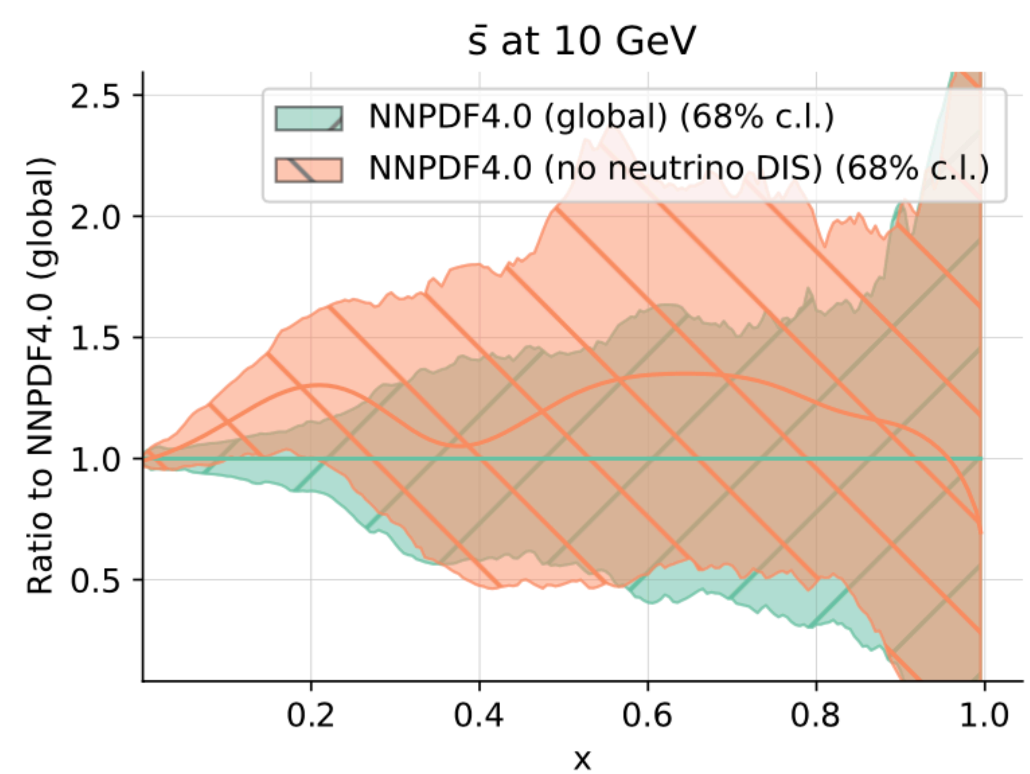
Neutrino DIS in (n)PDF fits

Neutrino DIS structure functions are a cornerstone of global nPDF fits

			Proton PDF sets				Nuclear PDF sets			
Data set		Ref.	ABMP16	CT18	MSHT20	NNPDF4.0	EPPS21	nCTEQ15	nNNPDF3.0	TUJU21
CHORUS $\sigma_{CC}^{\nu,\bar{\nu}}$	Pb	[1238]	✗	✗	✓	✓	✓	✗	✓	✓
CHORUS	Pb	[1239]	✓	✗	✗	✗	✗	✗	✗	✗
NOMAD $\mathcal{R}_{\mu\mu}$	Fe	[1195]	✓	✗	✗	(✓)	✗	✗	✗	✗
CCFR xF_3^p	Fe	[1240]	✗	✓	✗	✗	✗	✗	✗	✗
CCFR F_2^p	Fe	[1241]	✗	✓	✗	✗	✗	✗	✗	✗
CDSHW F_2^p, xF_3^p	Fe	[1242]	✗	✓	✗	✗	✗	✗	✗	✓
NuTeV $\sigma_{CC}^{\nu,\bar{\nu}}$	Fe	[1196]	✓	✓	✓	✓	✗	✗	✓	✗
NuTeV F_2, F_3	Fe	[1194]	✗	✗	✓	✗	✗	✗	✗	✗

Despite constraints on **quark flavour separation** from LHC, **neutrino DIS** still provides key information





Neutrino Structure Functions from GeV to EeV energies

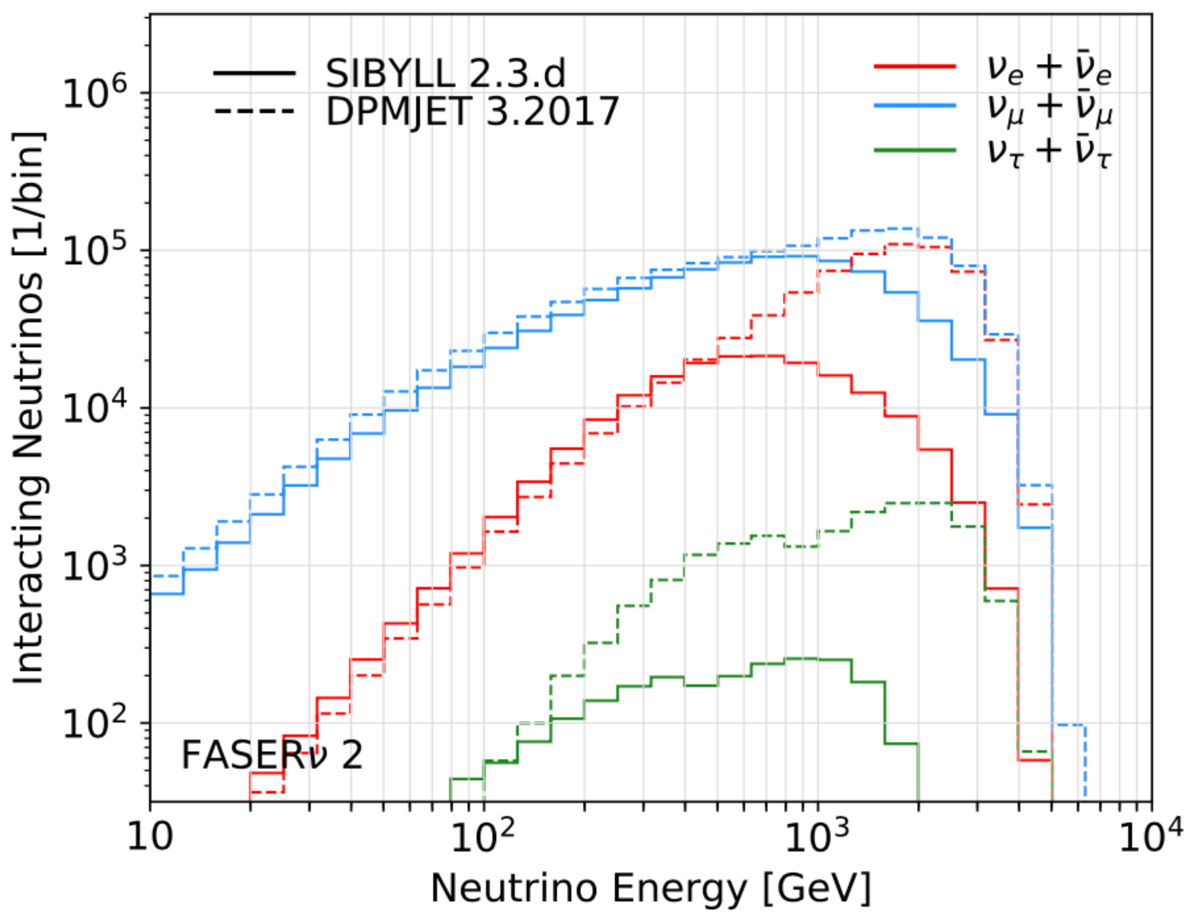
A. Candido, A. Garcia, G. Magni, T. Rabemananjara, J. Rojo, and R. Stegeman, in preparation

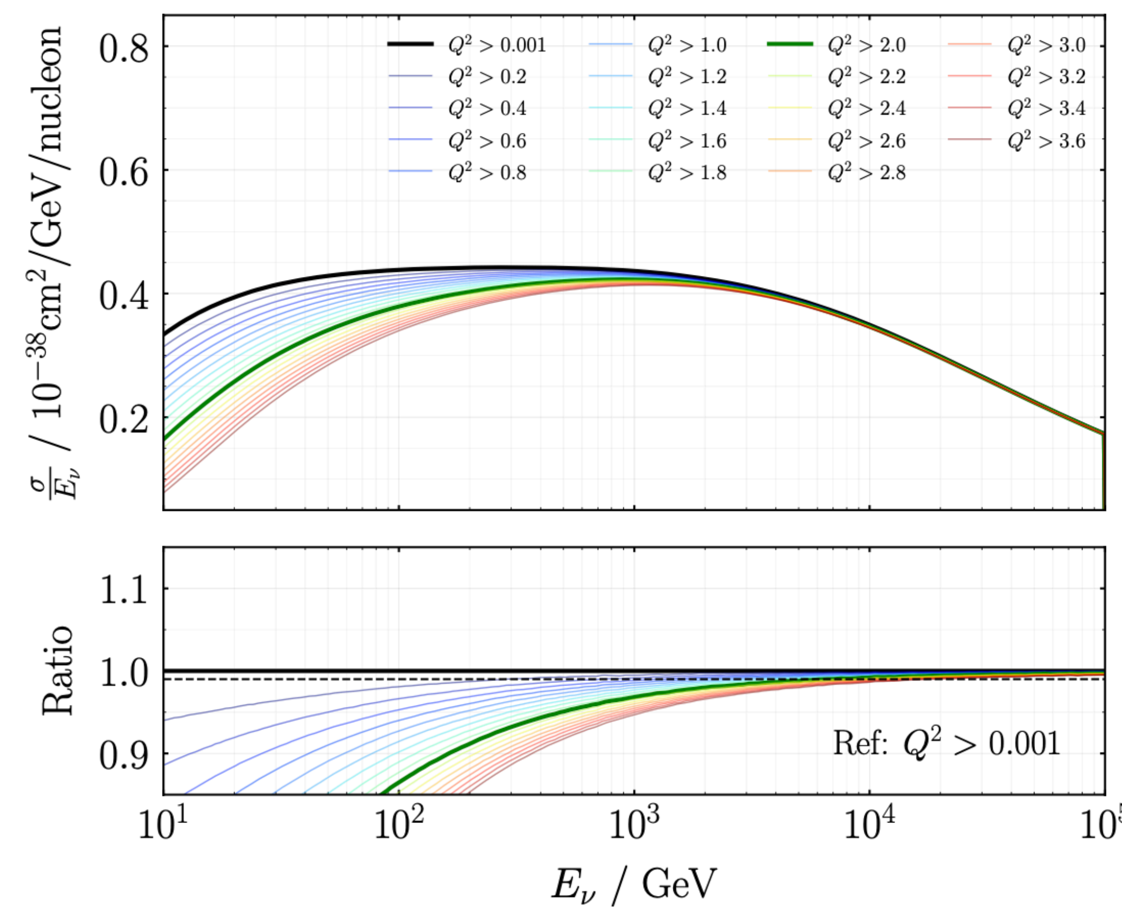
$$\frac{d^2\sigma^{\nu A}(x,Q^2,y)}{dxdy} = \frac{G_F^2 s/4\pi}{\left(1+Q^2/m_W^2\right)^2}\left[Y_+ F_2^{\nu A}(x,Q^2) - y^2 F_L^{\nu A}(x,Q^2) + Y_- x F_3^{\nu A}(x,Q^2)\right]$$

The role of the low-Q region

FPF neutrinos have **energy distributions** dominated by region **[100 GeV , 5 TeV]**.

How reliably can we predict their cross-sections and event rates?





inclusive cross-section receives **sizeable contributions from $Q < 2$ GeV region**, where structure functions cannot be evaluated in the pQCD framework

$$\sigma(E_\nu) = \int_{Q^2_{\rm min}}^{2m_N E_\nu} dQ^2 \left[\int_{Q^2/(2m_N y E_\nu)}^{1} dx \, \frac{d^2\sigma}{dx dQ^2}(x, Q^2, E_\nu) \right]$$

The role of the low-*Q* region

The **Bodek-Yang model** is popular to describe **low-*Q* inelastic neutrino DIS** structure functions

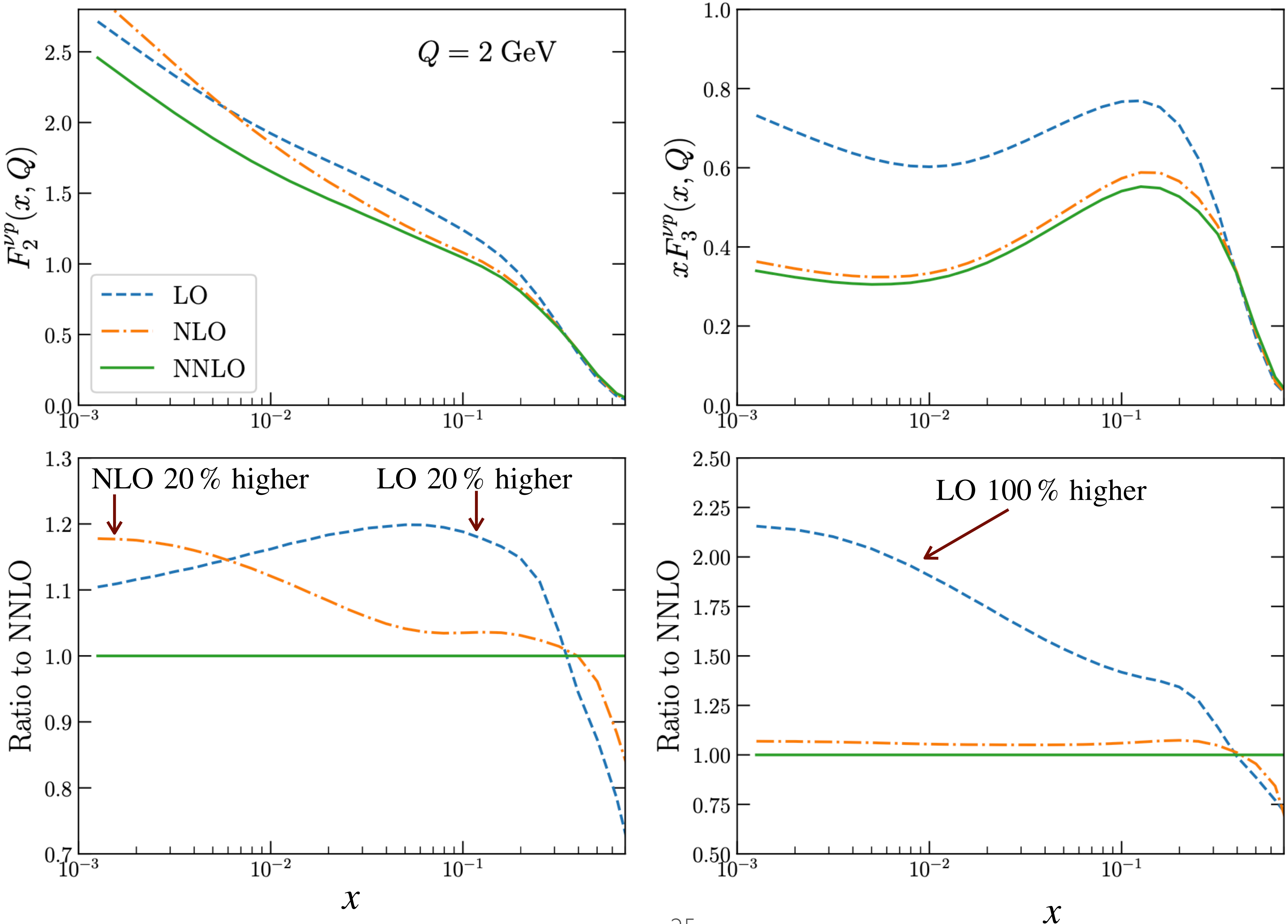
based on **effective leading-order PDFs** (GRV98LO) supplemented to phenomenological scaling variables and *K*-factors to improve agreement with data

$$f_i^{\rm LO}(x, Q^2) \to f_i^{\rm LO,BY}(\xi, Q^2) \qquad \xi = \frac{2x(Q^2 + m_f^2 + B)}{Q^2\left[1 + \sqrt{1 + (2m_N x)^2/Q^2}\right] + 2Ax}$$

Limitations of the BY model of neutrino structure functions:

- Obsolete PDF parametrisation that **ignores constraints from the last 25 years**
- Neglects **higher-order QCD corrections** (can be up to 100%)
- Does not provide **uncertainty estimate**, difficult to assess its accuracy and precision
- Cannot be systematically improvable e.g. by new data

The role of the low-Q region



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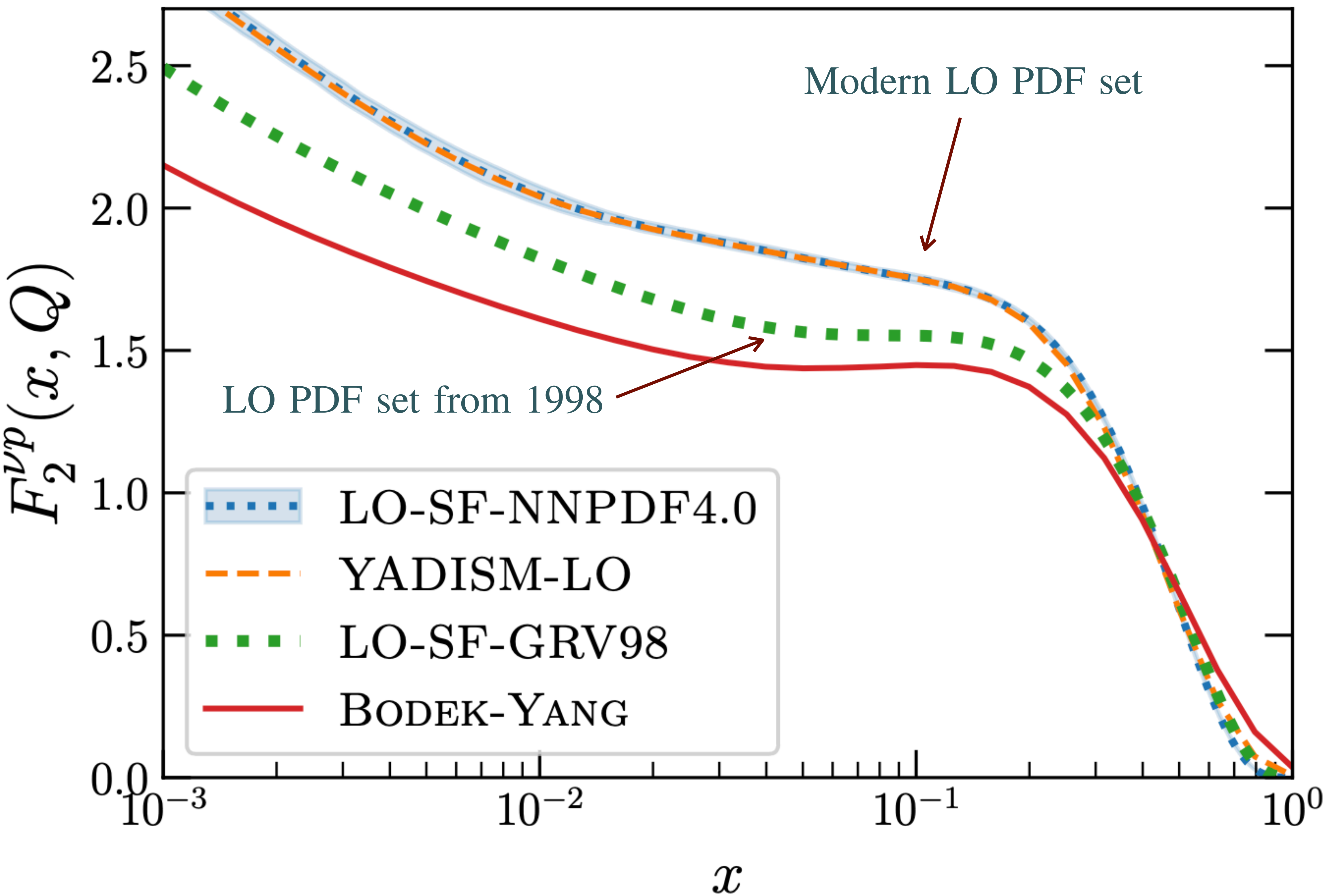
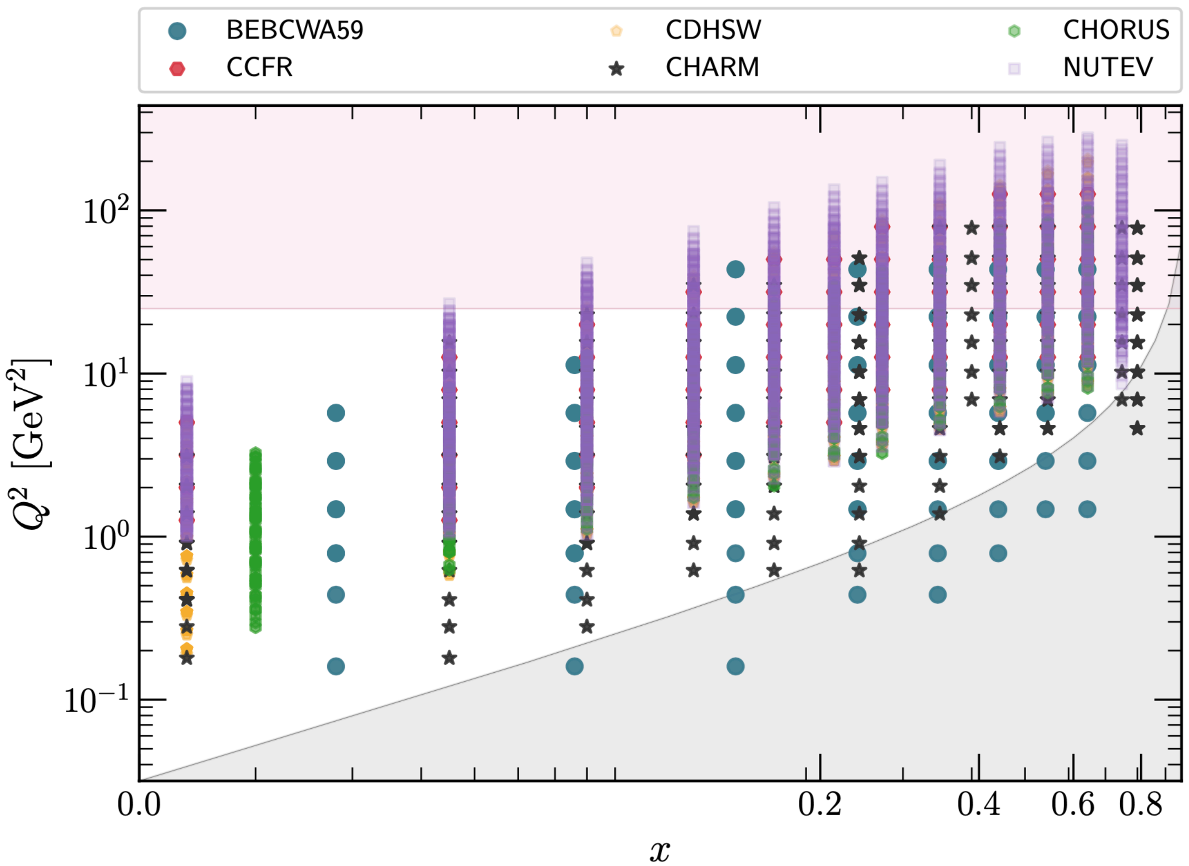
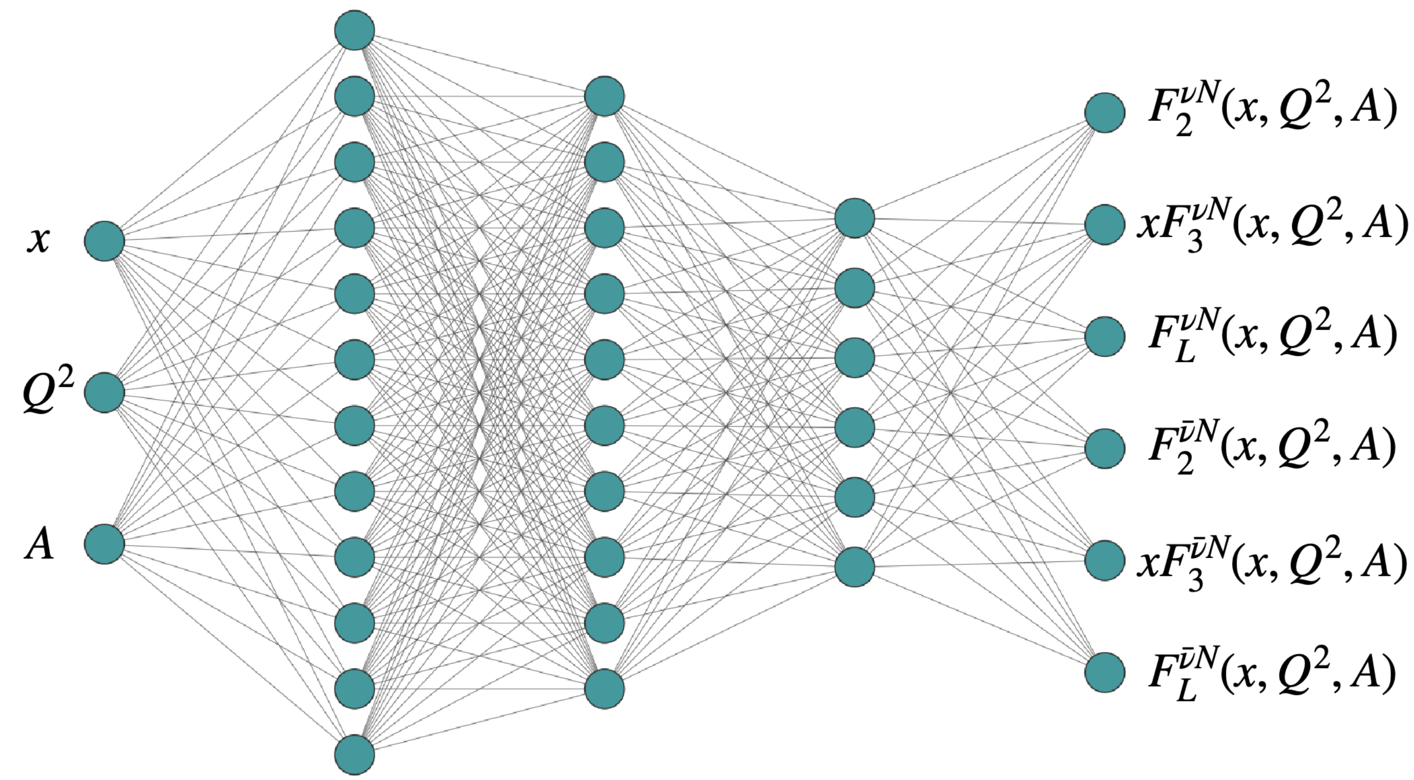


Bodek-Yang tends to GRV98 at large Q

The NNSFnu approach

- Use available data on neutrino-nucleus scattering to **parametrise and determine inelastic structure functions** by means of the NNPDF fitting methodology



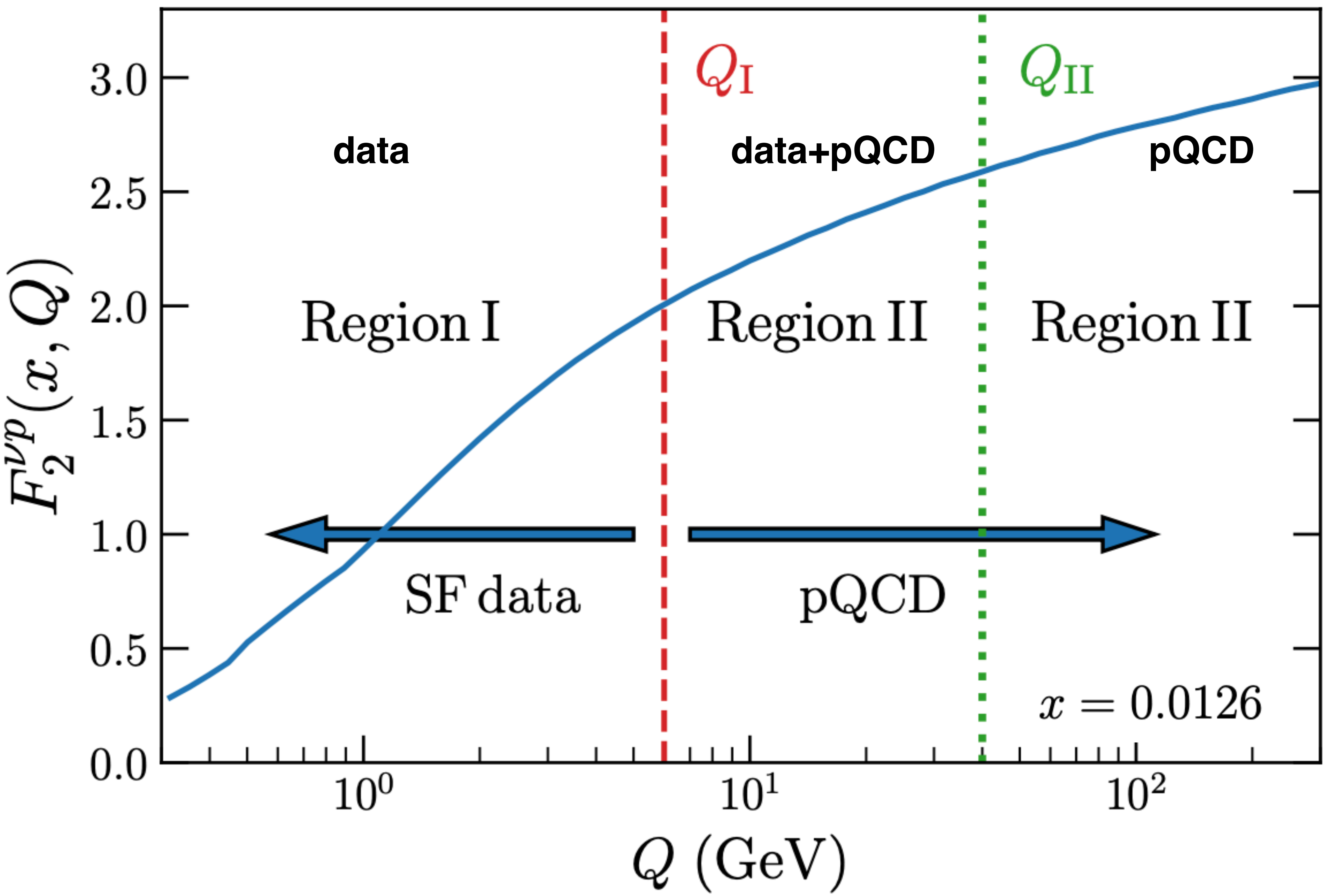


- This data-driven parametrisation is made to **converge to the pQCD calculation** for large enough Q^2 values as implemented with Lagrange multipliers

- In the neutrino energy region sensitive only to $Q >$ few GeV, **replace by pQCD calculation**

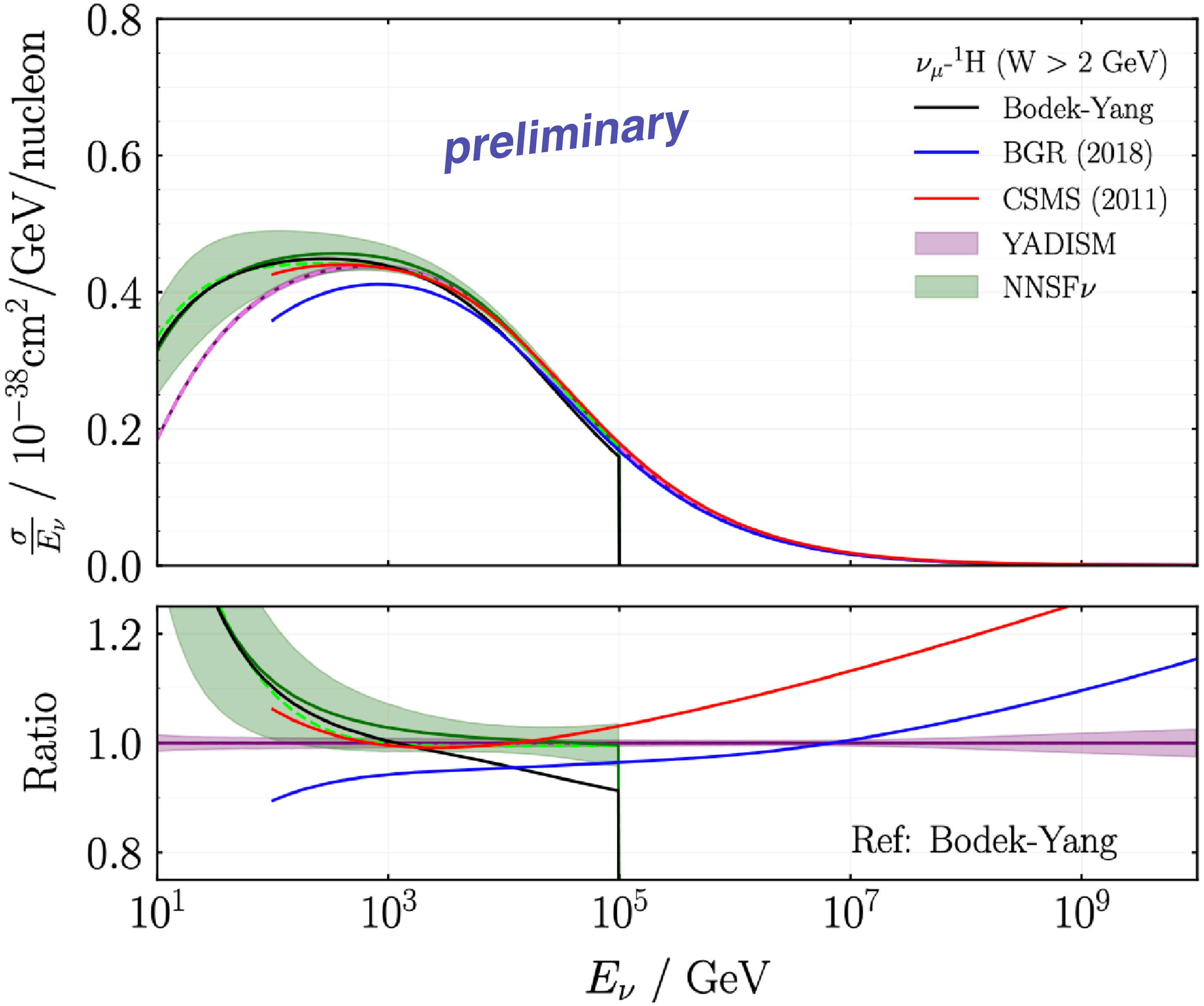
consistent determination of neutrino structure functions valid **for 12 orders of magnitude** from E_{nu} = few GeV up to $E_{nu}=10^{12}$ GeV

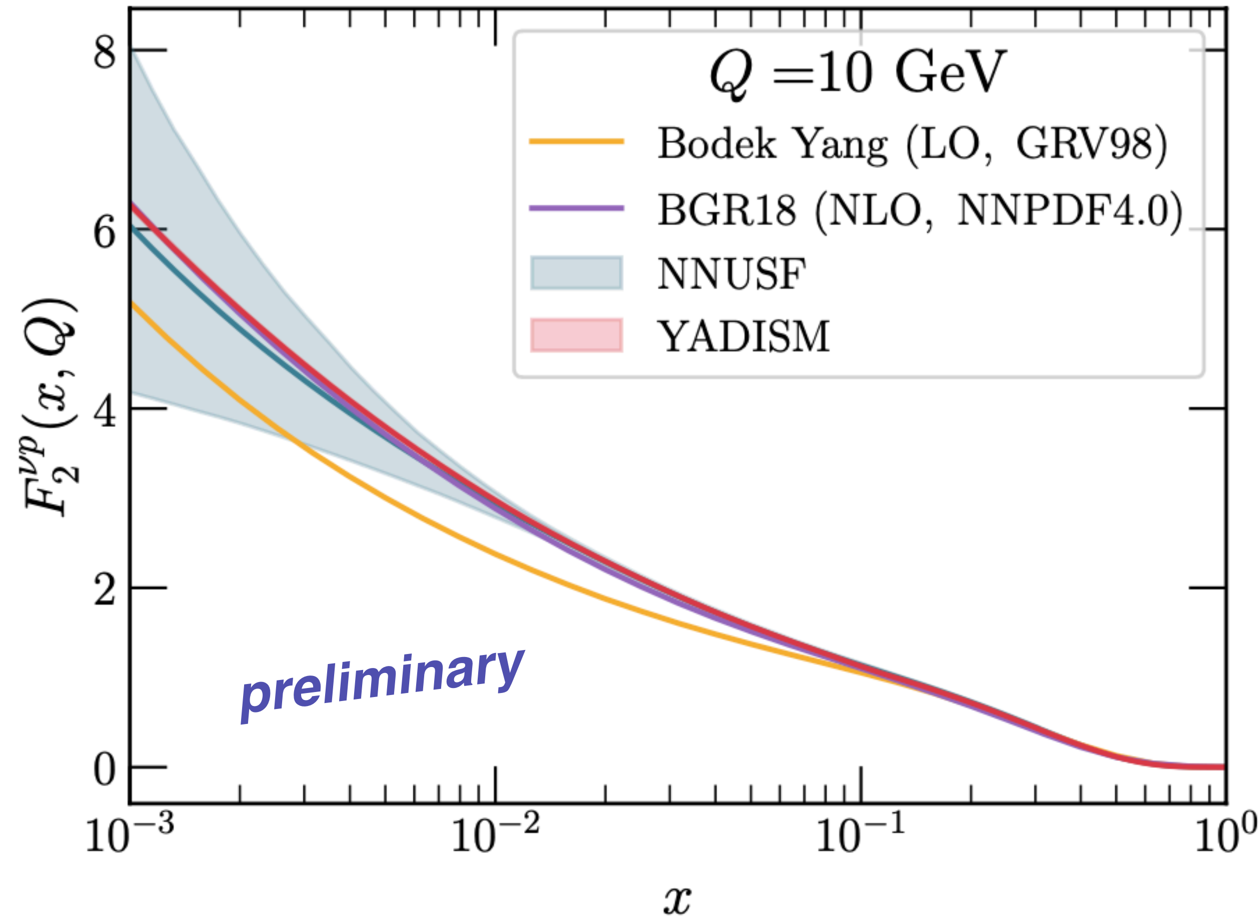
The NNSFnu approach



consistent determination of neutrino structure functions valid **for 12 orders of magnitude** from E_{nu} = few GeV up to $E_{nu}=10^{12}$ GeV

Results





- **Smooth matching** between data-driven and pQCD regions, uncertainty estimate in whole energy range
- Structure functions and integrated cross-sections available via **user-friendly LHAPDF grids**
- For the first time, a **unique theory prediction** for neutrino inelastic scattering suitable for neutrinos with energies from a few GeV up to the multi-EeV region

Probing proton and hadron structure at the FPF

Towards realising the FPF

- With the goal of delivering several **Conceptual Design Reports** (facility, experiments, physics case) of the FPF by 2023/2024, working groups have been created to focus on the key topics

ORGANIZATIONAL INFRASTRUCTURE

- New working group structure established to organize the work and provide contact names for new people interested in the FPF.

Steering Committee: Jamie Boyd, Jonathan Feng, Felix Kling

WG0 Facility: Jamie Boyd

Physics WGs

WG1 Neutrino Interactions: Juan Rojo

WG2 Charm Production: Hallsie Reno

WG3 Light Hadron Prod: Luis Anchordoqui, Dennis Soldin

WG4 BSM: Brian Batell, Sebastian Trojanowski

Detector WGs

WG5 FASER2: Josh McFayden

WG6 FASERnu2: Aki Ariga, Tomoko Ariga

WG7 FLArE: Jianming Bian, Milind Diwan

WG8 AdvSND: Giovanni De Lellis

WG9 FORMOSA: Matthew Citron, Chris Hill

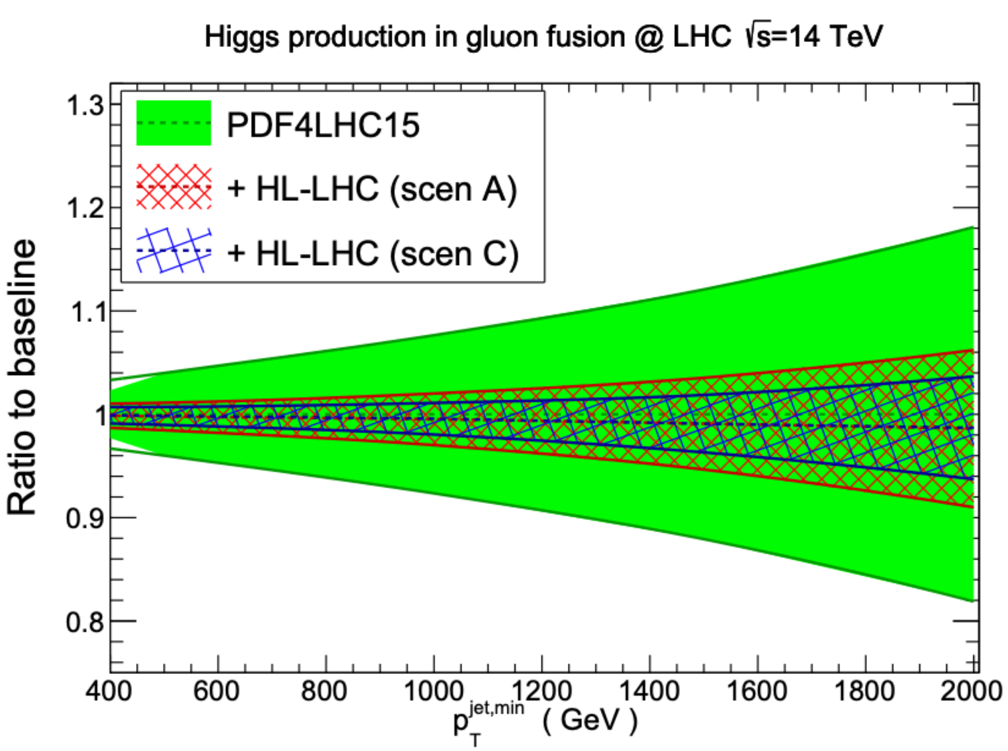
- The goal is to move from **qualitative** to **quantitative** estimates of the FPF scientific potential, including data projections and sensitivity curves, based on realistic detector coverage and performance

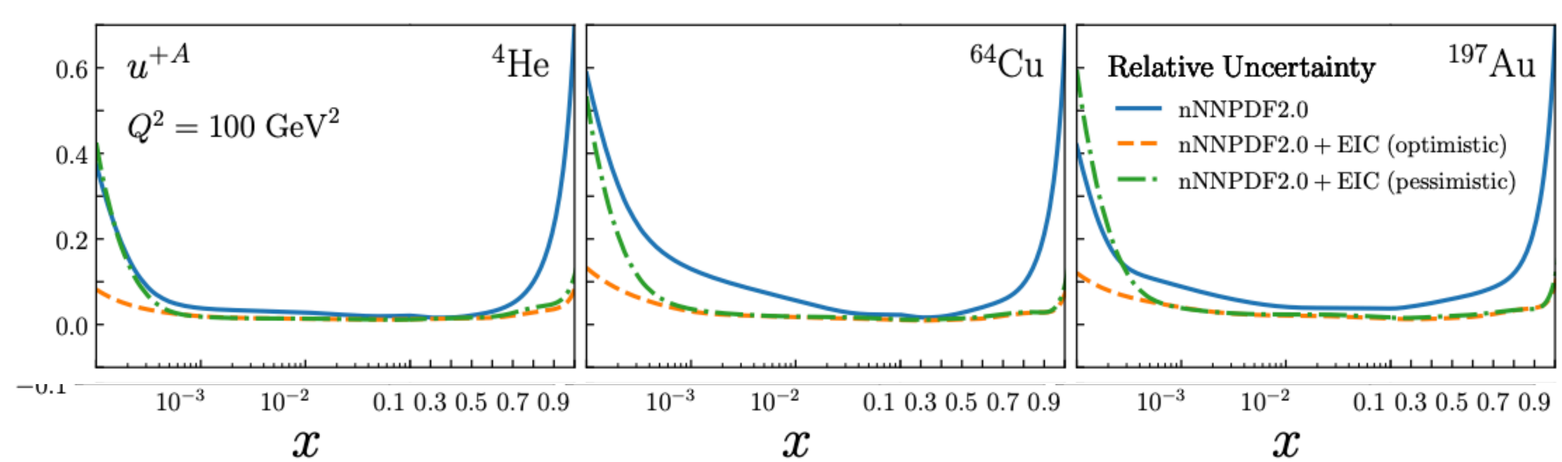
Everyone interested to contribute is welcome, get in touch if you want to join the FPF team!

FPF-WG1 goals

Quantify the potential of the **high-energy neutrino beams** of the FPF to **constrain proton and hadron structure** via the deep-inelastic scattering process

- For each FPF experiment, determine **acceptance and coverage in *(x,Q)* plane**
- Estimate the number of **expected DIS events** for each bin in the *(x,Q)* plane (statistical errors)
- Estimate **systematic errors** from expected detector response
- Generate **FPF DIS pseudo-data** using state-of-the-art pQCD calculations and include in *i)* proton and *ii)* nuclear PDF fits using **public** (e.g. xFitter, NNPDF, reweighting/profiling) and **private fitting tools**





building upon past expertise on related HL-LHC & EIC projections

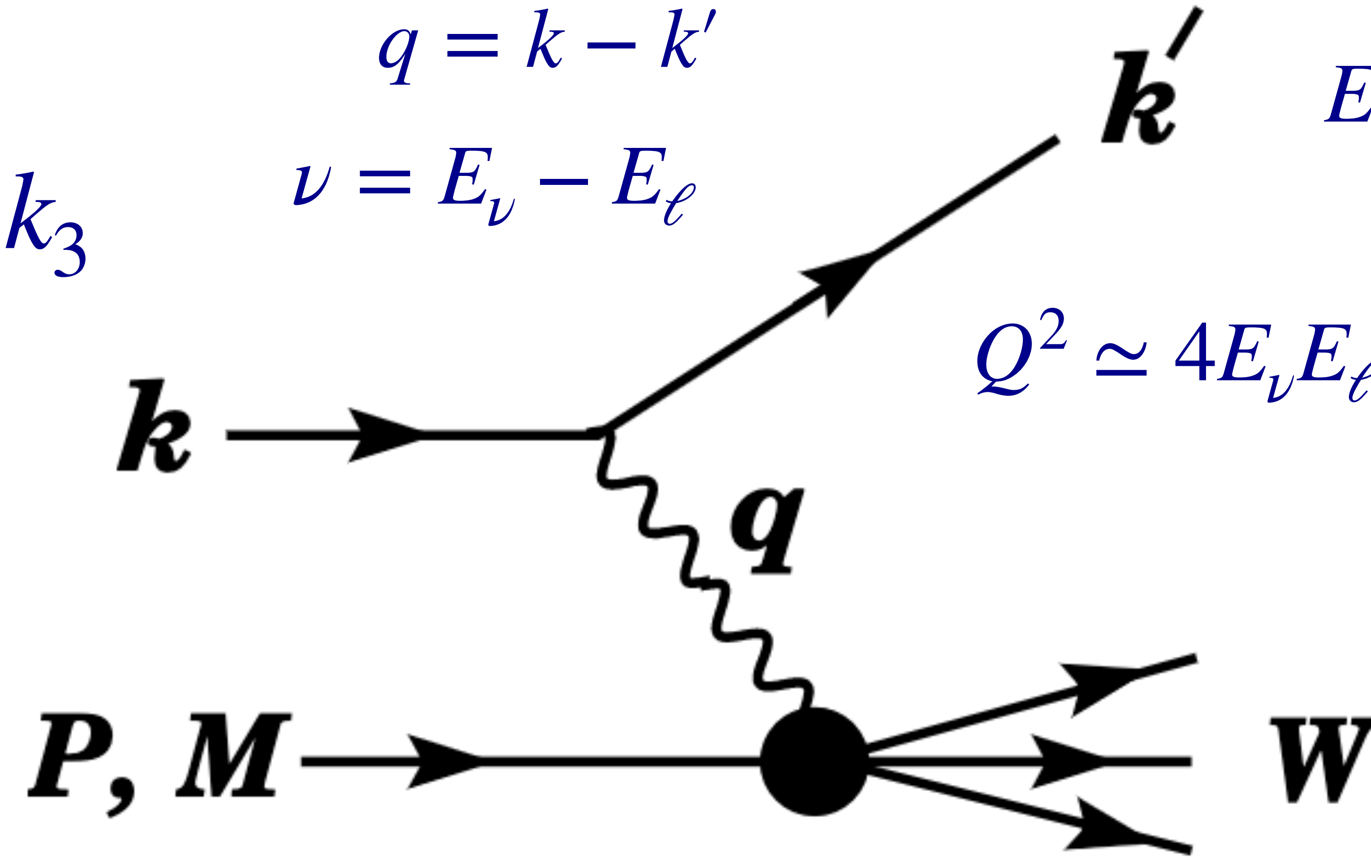
Deep-inelastic scattering @ FPF

$$q = k - k'$$

$$\nu = E_\nu - E_\ell$$

$$E_\nu = k_0 = k_3$$

$$E_\ell = k'_0$$



$$Q^2 \simeq 4E_\nu E_\ell \sin^2(\theta/2)$$

$$y = \frac{\nu}{E_\nu} = 1 - \frac{E_\ell}{E_\nu}$$

$$E_h = E_\nu - E_\ell$$

$$x = \frac{Q^2}{2m_N \nu}$$

$$W^2 = Q^2 \frac{(1-x)}{x} = m_N^2 + 2m_N\nu - Q^2$$

- At the FPF the **flux and flavour of the incoming neutrinos depends on the energy**: we can either take it from existing calculation or constrain it from the data
- Focus on **charged-current inclusive scattering**, with a single charged lepton in final state. Extend to semi-inclusive processes (e.g. **dimuon production**) afterwards
- Model how each experiment measures final-state particles to **reconstruct the DIS kinematics**

Deep-inelastic scattering @ FPF

- Assume that we can access the **outgoing charged lepton energy**, the **lepton scattering angle**, and the **total hadronic energy or invariant mass of the hadronic final state**

$$\left(E_\ell,\ \theta,\ W^2\right) \quad \text{or} \quad \left(E_\ell,\ \theta,\ E_h\right)$$

- Then we can reconstruct **Bjorken-*x*, momentum transfer square**, and **incoming neutrino energy**

$$\left(x,\ Q^2,\ E_\nu\right) \quad \text{or} \quad \left(x,\ Q^2,\ y\right)$$

by using the following equations

$$E_h = E_\nu - E_\ell$$ → fixes neutrino energy

$$Q^2 \simeq 4E_\nu E_\ell \sin^2(\theta/2)$$ → fixes four-momentum transfer

$$x = \frac{Q^2}{2m_N(E_\nu - E_\ell)}$$ → fixes Bjorken-*x*

nb ideally we'd like to over-constrain the kinematics by measuring more variables than unknowns

Deep-inelastic scattering @ FPF

- Given the DIS kinematics of an event, the interaction probability will be proportional to the **double-differential DIS cross-section**

$$\frac{d^2\sigma^{\nu A}(x,Q^2,y)}{dxdy} = \frac{G_F^2 s/2\pi}{\left(1+Q^2/m_W^2\right)^2}\left[(1-y)F_2^{\nu A}(x,Q^2) + y^2 x F_1^{\nu A}(x,Q^2) + y\left(1-\frac{y}{2}\right)xF_3^{\nu A}(x,Q^2)\right]$$

$$\frac{d^2\sigma^{\nu A}(x,Q^2,y)}{dxdy} = \frac{G_F^2 s/4\pi}{\left(1+Q^2/m_W^2\right)^2}\left[Y_+F_2^{\nu A}(x,Q^2) - y^2 F_L^{\nu A}(x,Q^2) + Y_- xF_3^{\nu A}(x,Q^2)\right]$$

- Traditionally neutrino measurements are presented at the level of individual structure functions, but this requires extra assumptions: cleaner to measure directly the **reduced cross-section**

- The number of events in a given bin will be given by

$$N_{\rm ev}(x\in[x_{\rm min},x_{\rm max}],Q^2\in[Q^2_{\rm min},Q^2_{\rm max},E_\nu\in[E_{\nu,\rm min},E_{\nu,\rm max}]) \propto \int_{x_{\rm min}}^{x_{\rm max}} dx \int_{Q^2_{\rm min}}^{Q^2_{\rm max}} dQ^2 \int_{E_{\nu,\rm min}}^{E_{\nu,\rm max}} dE_\nu \frac{d^2\sigma(x,Q^2,E_\nu)}{dxdy} f(E_\nu)$$

experiment-dependent factor ***scattering cross-section*** ***incoming neutrino flux***

- Work in progress will result in **dedicated set of FPF pseudo-data** that will be input to global fits of proton and nuclear PDFs

Realising the Forward Physics Facility

The road ahead

- The unique SM and BSM physics potential of the FPF relies on the high CoM energy of the LHC: **unless it is realised at the HL-LHC it will disappear for decades** (or forever)!
- Strong alignment with **EPPSU** (2020) and **Snowmass** (2022) priorisation

2020 EPPSU 1st Recommendation

The successful completion of the high-luminosity upgrade of the machine and detectors should remain the focal point of European particle physics, together with continued innovation in experimental techniques. The full physics potential of the LHC and the HL-LHC, including the study of flavour physics and the quark-gluon plasma, should be exploited.

2022 Snowmass Energy Frontier Summary

Our highest immediate priority accelerator and project is the HL-LHC, the successful completion of the detector upgrades, operations of the detectors at the HL-LHC, data taking and analysis, including the construction of auxiliary experiments that extend the reach of HL-LHC in kinematic regions uncovered by the detector upgrades.

Resource needs and plan for the 5-year period starting 2025:

1. Prioritize HL-LHC physics program, including auxiliary experiments.

- Strong support from **CERN**, **LHCC**, and **Physics Beyond Collider** (PBC) group

C. Vallee, PBC workshop 11.2022

FORWARD PHYSICS FACILITY

Good progress in the conceptual design of the infrastructure and decoupling from LHC operation constraints

Strong support from Snowmass HE group to HL-LHC auxiliary detectors

LHCC statement in September recommending to further study the FPF in the global PBC context

Next steps:

- **CDR expected in 2023 with more details on detector technical aspects, physics complementarity and Collaboration structure**
- **Relevant information on physics reach (sensitivity curves, etc…) to be provided to FPC, BSM and QCD WGs to address comparison with other projects**

- Building a strong, focused, and diverse community of particle physicists interested in FPF
- Strong synergies with other next-generation facilities, such as the **Electron-Ion Collider**

Summary and outlook

- The FPF would realise an exciting program in a broad range of topics from **BSM and long-lived particles** to **neutrinos, QCD, and hadron structure**, with connections to astroparticle physics

- The FPF would continue the long tradition of neutrino DIS @ CERN **now with TeV beams**

- **High-energy neutrino DIS** would open a new probe to proton and nuclear structure, complementing existing and future experiments, e.g. CC DIS complements the **EIC**

- Charm meson and light hadron production in the forward region represent a **testbed for QCD calculations**: higher-orders, BFKL, fragmentation, non-linear effects, small-x PDFs, …

- A **machine learning parametrisation of neutrino structure functions** can improve the reliability of theory predictions for event rates at the FPF

FPF Forward Physics Facility

Extra Material

Input from experiments

	lepton energy E_l	lepton angle θ	charged lepton sign	hadronic final state
FaserNu2	$E_l > 100$ GeV $\delta E_l = 30\%$	$\tan(\theta) < 0.5$ $\delta\theta = 1$ mrad	Yes, for muons	E_h accessible, charm ID possible, $\delta E_h = 30\text{-}50\%$
AdvSND@LHC	$E_l > 20$ GeV (muon)	$\theta < 0.15$ rad (muon) $\theta < 0.5$ rad (electron, tau)	Yes	E_h accessible
FLArE	$E_l < 1$ TeV, $\delta E_l = 5\%$ (electron) $E_l < 2$ GeV (muon)	$\theta < 0.5$ rad, $\delta\theta = 15$ mrad (electron) $\theta < 0.4$ rad (muon)	Maybe, for muons	E_h accessible, $\delta E_h = 30\%$

exploit complementary of FPF experiments for hadron structure studies & provide input for experiment design at the light of **DIS & PDF requirements**